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STATE-OF-THE-ART OF MICROSEISMIC APPLICATION FOR MINING

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January 1986

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100 pp

ENERGY RESEARCH PROGRAM
COAL RESEARCH LABORATORIES
DIVISION REPORT ERP/CRL 86-1(TR)

MICROMEDIA

86-03506/

MICROFICHE

pp. 98

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by

T.I. Vladut*

ABSTRACT

The report is a state-of-the-art review on the use of microseismic technology for the mining industry. The review was done with a view of evaluating the potential usage of microseismic technology in mining activities for the actual state of the industry and future requirements. Some of the basic physical elements of microseismic technology are discussed as a background for mining professionals. The report focuses mainly on the physical explanation. The core of the report focuses on five areas of usage of microseismic monitoring, underground hard rock mining including rockburst application, soft rock mining including coal and application for open cast operations. A brief review is included on the potential contribution of laboratory scale microseismic measurements. The report reviews equipment specification, installation problems and the economical aspects of implementation of microseismic monitoring. Several aspects of the concept of utilization of microseismic monitoring for early warning are addressed in parallel with the aspect of the physical nature of the microseismic and seismic activity as a man-made phenomena.

The view of the author is the results of an extensive technical literature review which is referenced by three bibliographical data basis. The reviewer has hand-on experience with the utilization of microseismic technology for mining and civil engineering application.

The report is intended as a preliminary data base for mining professionals who are considering the utilization of microseismic technology in mining applications.

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APPLICATION DES TECHNIQUES MICROSÉISMIQUES DE POINTE À L'INDUSTRIE MINIÈRE

par

T.I. Vladut*

RÉSUMÉ

Dans ce rapport, l'auteur présente les résultats d'une étude portant sur l'utilisation de la technologie microséismique dans l'industrie minière. L'étude a été effectuée en vue de faire une évaluation des possibilités liées à l'utilisation des techniques microséismiques dans l'industrie minière en fonction des besoins actuels et futurs de l'industrie. Certains des éléments physiques fondamentaux de la technologie microséismique sont étudiés en tant que données de base à l'usage des exploitants de mines. Le rapport porte principalement sur l'explication des aspects physiques de la technologie. Le corps du document est consacré à l'étude de cinq domaines où la surveillance microséismique est utilisée, notamment pour la surveillance des travaux d'exploitation de roches dures incluant le monitorage microséismique des coups de toit, la surveillance des travaux d'extraction de roche tendre y compris le charbon et l'application des techniques au procédé de coulée à découvert. Il comporte également une brève étude des contributions possibles des mesures microséismiques effectuées en laboratoire. Le rapport porte sur les spécifications relatives à l'équipement, les problèmes reliés à l'installation et les aspects économiques de la mise en oeuvre de la surveillance microséismique Plusieurs éléments liés à l'application de la surveillance microséismique des dispositifs de première alerte sont étudiés en corrélation avec les éléments liés à la nature physique de l'activité microséismique et séismique en tant que phénomène artificiel.

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L'opinion de l'auteur est fondée sur les résultats découlant d'une étude exhaustive de la documentation technique mentionnée dans trois bases de données bibliographiques. L'auteur possède une expérience de première main dans l'application des techniques microséismiques à l'industrie minière et dans les travaux d'ingénierie civile.

Le rapport se veut une source de données préliminaire pour les gens de métier qui envisagent l'application des techniques microséismiques à l'industrie minière.

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1. INTRODUCTION

Several large scale microseismic monitoring systems operate in Canadian mines and the number of mining operations considering the use of microseismic monitoring systems are increasing (1). This report is a state-of-the-art summary on microseismic technology. It presents realistic expectations and potential problems which may be encountered while developing sound programs for mining applications.

The report is designed for mining professionals. It should be used as a source of background material and as an introduction to preliminary reference information related to the use of microseismic technology.

Monitoring of microseismic activity (MA) or acoustic emission (AE) associated with mining activities began in 1938 with the early experiments of L. Obert and W. Duvall at lead-zinc mines in Northeastern Oklahoma. The accidental discovery of microseismic emissions in these mines has led to the development of a detection MA method which is widely used in relation to mining safety.

During the last decade, further developments in microseismic monitoring are best reflected in three International Conferences organized by Professor H. Reginald Hardy, Jr. and F.W. Leighton at Pennsylvania State University (2). Better understanding has been achieved because of the variety of MA applications used in other fields such as petroleum, gas, underground waste disposal, civil engineering and avalanche control.

In mining, microseismic monitoring applications are increasing. However, in this respect, ground control for improved safety appears to be the principal area. The effectiveness of mechanical mining is highly influenced by geomechanical disturbances and their advance detection is expected to be improved through microseismic monitoring. This is why many Canadian mines are using MA techniques. Extensive participation by the Canadian mineral industry in two Sudbury symposiums on microseismic monitoring indicates a great deal of interest.

At the 1984 symposium, various types of microseismic measurements in approximately seventeen mines were discussed (3). This is in keeping with similar development throughout the world and is exemplified in this report. Many of these applications are designed to reduce the hazards of rock bursts.

Microseismic signals are also monitored in other areas of rock failure such as evaluating slope stabilities in surface mining operations.

The Canadian contribution in utilization of microseismic technology is summarized by J.E. Udd and D.G. Hedley (1) in their submission to the provincial inquiry into ground control and emergency preparedness in Ontario mines (1985). Major contributions from CANMET (Canada Centre for Mineral and Energy Technology) arose throughout the years beginning in 1966 by Y.S. Yu (4), more recently by K. Barron (1970). Several experimental applications in monitoring were undertaken in Ontario in 1963 by D.F. Coates (5) and more recently at McLeod, Wawa (6), and Quirke mines (7) as well as many others (8-33).

Extensive references to all aspects of microseismic and acoustic emission technology are in a master bibliography published by the Proceedings of the Third Conference held in 1981 (2). Additional references, not given in the master bibliography, are referenced in the bibliography of this report (Appendix A)*. This report reviews the most important applications used in mining.

Some of the chapters of this report may not be of general interest to all mining personnel (such as the chapter which details the theoretical aspects of microseismic emissions). The report focuses mainly on the physical explanation rather than mathematical expressions. Only a few mathematical expressions are given in the body of the report and the physical definitions are referenced in special appendices.

Due to the fact that in microseismic monitoring common terminology is used for acoustic emission, an extensive standard definition of terms has been included in Appendix B.

This report is intended to be a quick reference for mining professionals on current MA technology and applications and presents general concerns related to the increase of seismic activities in deep mining developments.

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*Note on bibliography. Three types of sources of information are used in this report and are detailed in the first page of the Appendix A.

2. BACKGROUND ON MICROSEISMIC MONITORING

2.1. MICROSEISMIC MONITORING AS A GEOPHYSICAL METHOD

Acoustic emissions resulting from rock fractures and rock movements are detectable signals in rock bodies near the energy source. Microseismic energy is generated when stresses accumulated in rock formations are released in the form of fracture development.

Monitoring acoustic emissions has the some benefits and disadvantages as other geophysical methods. Geophysical methods monitor modifications of natural or induced fields. As a whole geophysical methods measure the modifications of specific fields to evaluate the properties or state of the rock body subjected to a natural or induced field.

Referring on the properties or rock body shape, size or location, suppositions are made related to selected parameters.

It should be underlined that geophysical measurements focus on a single type of information and is supposed to provide several characteristics of the disturbing body.

The most common information in prospective geophysics is related to defining the shape of a disturbed rock body and information about the effect of the disturbance on the rock properties.

Because of the uncertainties related to an interpretation based of one type of information (geophysical) while there are several characteristics, hypotheses are made to obtain a solution to the objective of the investigation.

Commonly methods used to solve uncertainties related to geophysical information use several different types of geophysical measurements.

For example, in mining applications there is parallel use of seismic and electric measurements to estimate the excavatability of ground material (Fig. 1). Two other examples are mineral body identification and physical property assessment. Quite often utilization of different types of geophysical methods may encompass utilization of both natural and induced field measurements.

It should be noted that equipment generally observes the geological rock body under steady conditions. Geological observations of formations under going structural changes may be evaluated according to the initial conditions and assessed by initial measurements. Structural development may

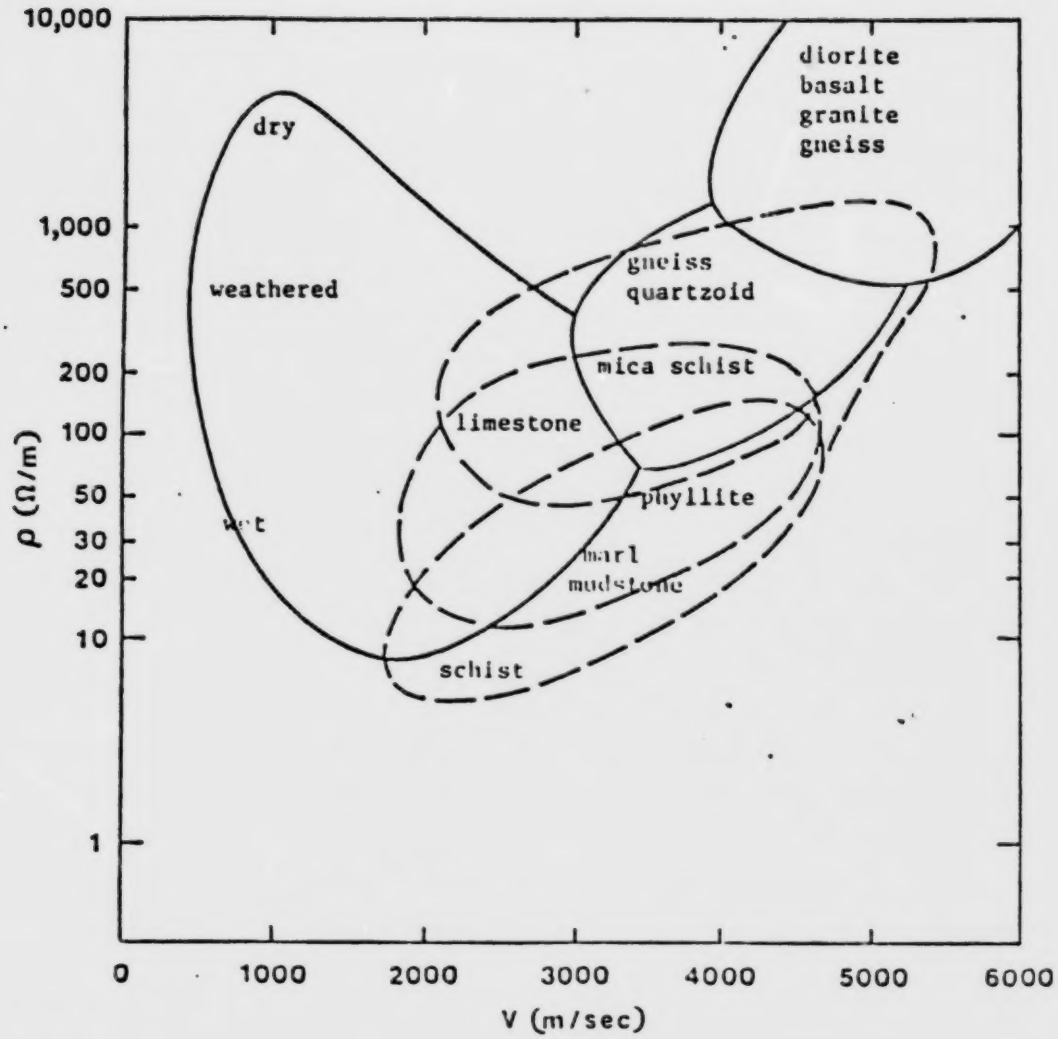


Fig. 1 - Utilization of geophysical methods for evaluation of rock excavability (36). Geophysical data: vertical scale - resistivity, horizontal scale - seismic velocity

be of a mining or extractive nature. A typical situation is fluid extraction, such as in oil production, where the modifications are generated by the progress of steady depletion.

Problem solving utilizating a single geophysical method or using multitude methods requires correct interpretation of data.

Defining a geological bod is related to:

1. the contrast of physical properties which are measured,
2. the volume and orientation of the observed body in relation to the measurement, and
3. the distance between the perturbing body and the point of observation.

Three suppositions should be made when utilizing geophysical measurements:

1. The monitored disturbance has a significant value pertinent to the geophysical method which is used for investigation.
2. The interpretation of the physical meaning of a measurement is related to the knowledge of the geological setting of the observed body.
3. For bodies subjected to continuous modification, as generated by mining extraction, interpretation of changes in geophysical parameters are related to the knowledge of the induced variations by the mining operation.

2.2. PRINCIPLE OF ACOUSTING MONITORING

Discovery of microseismic emission was accidental (111) and, at first, the significance of the discovery was not recognized. The discovery was made in a lead-zinc mine in northeastern Oklahoma in 1938 during experiments to determine if seismic velocity in mine pillars was dependent on the pillar load.

The fact that the microseismic signals are caused by stress, even in perfectly stable pillars, was later discovered by tests in an northern Michigan copper mine.

Microseismic emissions are generated at high stresses and the detection of the emissions does not require knowledge of the mechanical properties of the rock or the state of the stress in the rock body.

Rock under stress reacts in small incremental adjustments to reach a new state of equilibrium. Eventually the adjustments become more frequent and are characterized by a release of seismic or audible energy. Simple and relevant procedures reveal stress modification of the rock and rock response is by counting the number of emissions associated with the load adjustments. As the load increase reaches its ultimate strength (Fig. 2), there is an increase in the number of signals, Obert (1945).

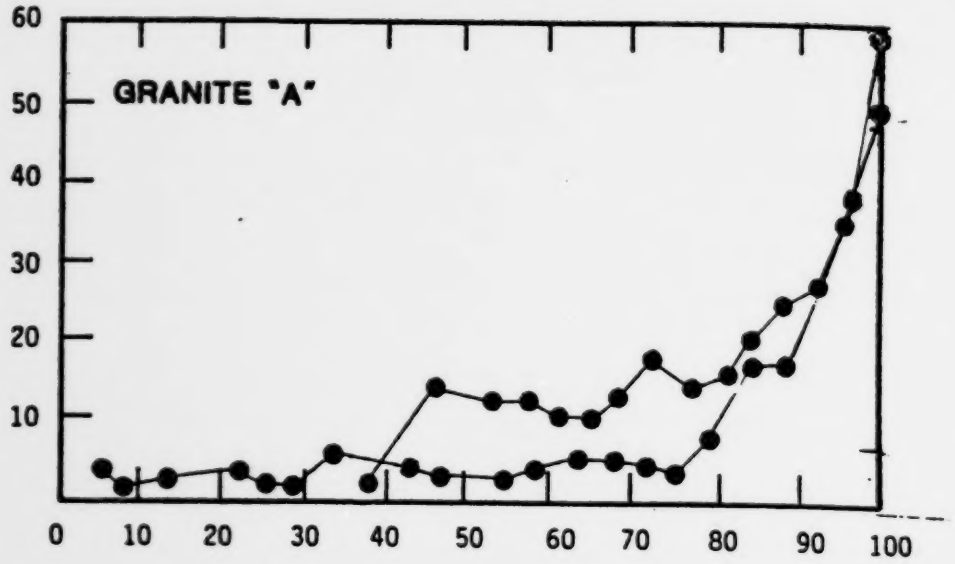
In recent years, microseismic monitoring equipment (MA) has undergone significant improvements. MA equipment performs essentially the same functions as most seismic instruments. They all detect and record ground motions produced by sudden displacements or failure within a rock mass.

The instrumentation is composed primarily of three elements (a) transducer, (b) an amplifier and (c) a readout device recorder.

The Transducer (or more specifically a geophone) attached to the rock,moves as the ground responds to a seismic wave. The transducer identifieswave velocity or acceleration. Wave velocity and acceleration are second and third differentials at ground particle displacement. The geophone generates a voltage proportional to wave velocity and is constructed to respond to vertical andhorizontal vibrations. Geophone orientation should correspond to the direction of the monitored movement.

Amplifer Equipment and Readout Device Recorders are significant issues in the area of MA monitoring. Most instruments use a preamplifier located within the transducer. This is required to reduce noise and attenuation between the geophone and main amplifier. The recorders are data processing units which post-amplify and condition the signals. In most MA applications the geophone, or an array of geophones, is placed in or on the ground some distance away from the processing unit. The transmission of data between the processing unit and the geophones is by cable or by wireless transmission methods. With regards to wireless transmission a reference is made in this report to the microseismic instrumentation developed by Denver Research Centre of the U.S.B.M. which usessolar panels as a part of a total remote power system package (11).

Current information on equipment and procedures is very beneficial when selecting monitoring equipment. Though report does not focus on



I - Microseismic emission rate in events per minute

II - Applied load/ultimate strength in percent

Fig. 2 - Increase in microseismic activity prior to failure
Obert and Duval (1945)

equipment selection or state-of-the-art commentary on instrumentation development, it should be underlined that MA instrumentation is actually a well developed technology. A team consisting of a user/mining professional and a high-tech professional operator should select MA equipment for mining applications. The two elements to be considered are:

1. contacts with equipment manufacturers to evaluate system performance,
2. contacts other mines which have experience in the utilization of MA.

Support by high-tech professionals is essential when developing an MA system because there are specific problems related to calibration and operation. Other problems encompass trade-offs between sensitivity, frequency response, gain, distortion, stability and drift. The role of the mining professional is to decipher the variability of data and to correlate the seismic events with the failure process.

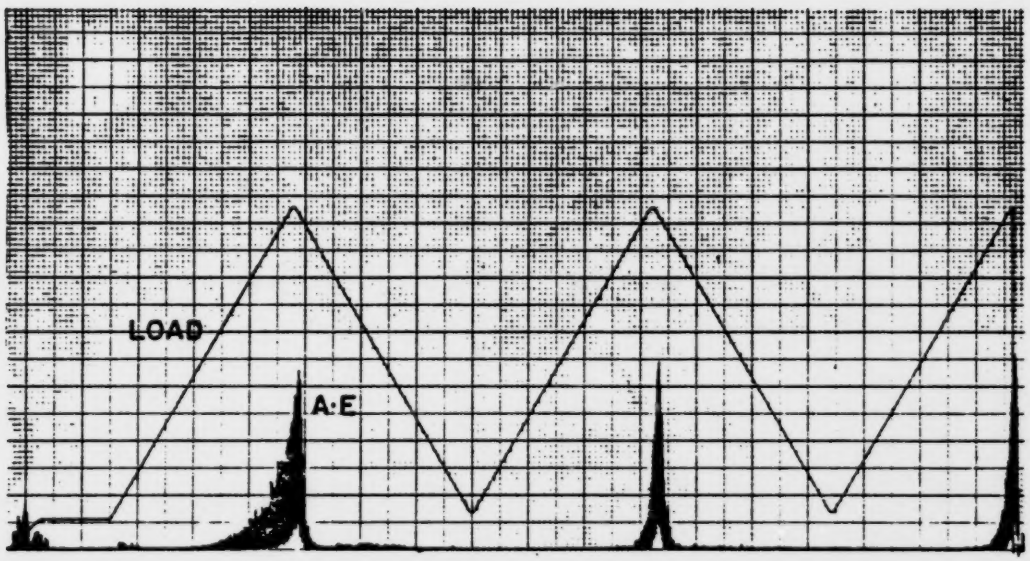
In MA monitoring the number of seismic events reduced to a convenient time rate (day/hour) is of fundamental significance. The understanding of the significance of the MA time-rates on the processes of physical failure within the rock body is fundamental. The relationship between MA rate and stress-strain graph, shold be determined a priority as it is important reference data.

Figure 3 is a laboratory example of MA monitoring on sandstone conducted to test rock fatique. Figure 4 is an example of slope monitoring and Fig. 5 is related to an application in an underground mine to study the phenomena of coal mine bounces and their relationship to MA.

MA terminology is of importance and has been developed to be used in non-geologic applications and material such as metals and ceramics. Utilization of such terms occasionally causes difficulties when dealing with geological materials. Details of ASTM definitions are found in Appendix B.

The principle of counting MA is simple and is related to the sensitivity of the system to discriminate high frequency emissions (1 to 10 000-Hz). MA like other failure related phenomena occurs in discrete increments irregularly spaced in time. A typical sample of such emission is indicated in Fig. 6

An important feature of any MA monitoring is to discriminate between rock failure and background noise. Background noise is generated from other acoustic sources associated with mining operations, laboratory testing machines, or the weather. Because of this interference high resolution



Relationship Between Acoustic Emission Rate and Loading Cycle. [Load, 100K lbs Full Scale, maximum 87.5% of Dynamic Strength, at 0.0025 cps; A.E./sec., at 35 db and 100K-300KHz; Chart Speed = 1"/min.]

Fig. 3 - Microseismic emission in laboratory testing (112)

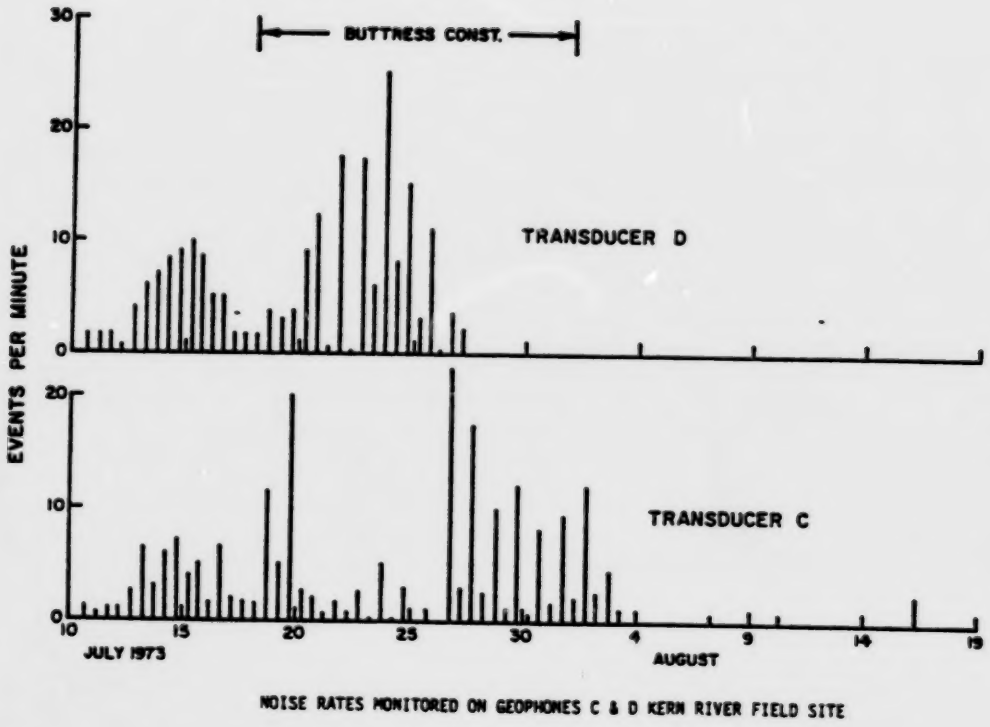
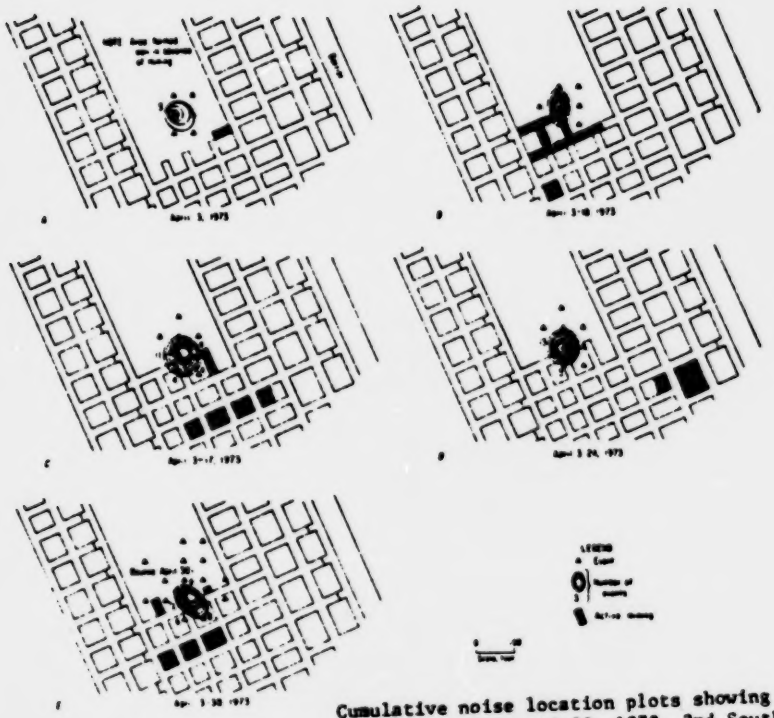
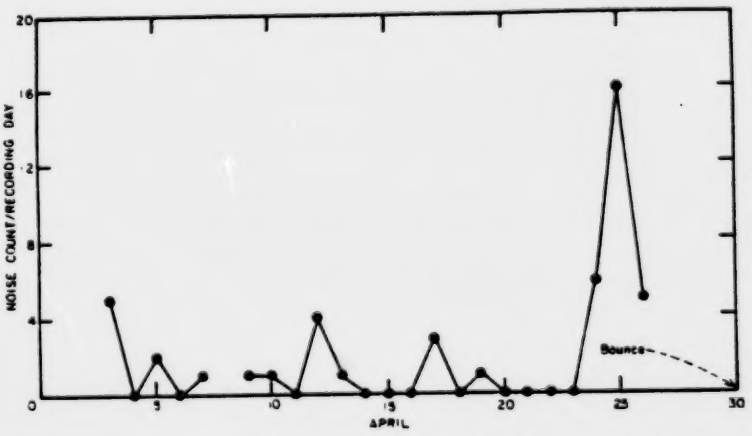


Fig. 4 - Utilization of field microseismic monitoring in a slope stabilization (127)

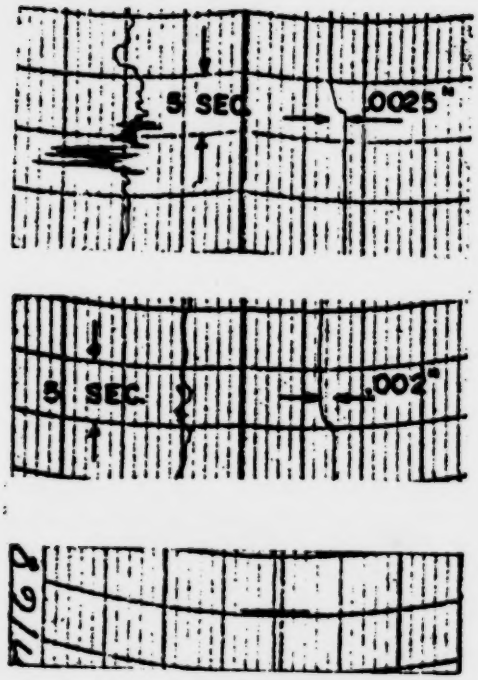


Cumulative noise location plots showing growth of bounce area of April 30, 1973, 3rd South.



Rock noise rate plot from bounce area of April 30, 1973, 3rd South.

Fig. 5 - Microseismic monitoring in a coal mine (124)



Examples of seismic "noise" associated with ground movement (top and centre), and a single microseismim (bottom). Chart enlarged 3x.

Fig. 6 - Typical recording of microseismic event (5)

observation equipment is required to detect rock noises and stress related emissions.

2.3. PARTICULARITIES OF MA GENERATED BY ROCK MATERIALS

Stress build-ups lead to microfracturing of the rock material and as tiny cracks develop or propagate along preferential paths, seismic energy is released which can be monitored. MA has five basic properties: wavelength, cycle, frequency, velocity and intensity (Appendix C). Some special features of the acoustic properties of rocks and the relationship to mechanical properties should be mentioned.

Propagation of seismic waves in rocks are a mainly elastic phenomena determined by rock density and elastic constants. These properties with the nature of the seismic wave (longitudinal, transverse, etc.) determine the velocity of propagation. As the wave emanules from a point source, it will decrease in intensity with distance and in addition there will be a real decrease in the total energy of the wave due to "friction" or "damaging" - the analytic properties of the rock.

The spectral nature of the source determines the frequency of waves produces and thus propagated. According to frequency, elastic waves are divided into infrasonic (under 20 Hz), audio (20 to 20 000 Hz), ultrasonic (more than 2×10^4 Hz) and hypersonic (more than 10^{10} Hz). Depending on the type of strains, since the elastic waves represent strain propagation, waves of different kinds may arise: P-waves longitudinal (compression) or S-waves transverse (shear strains)(Appendix C).

The velocity of elastic waves is determined by the elastic constants and the density of the rock in which they are propagated (Appendix C).

Velocity does not in practice depend on frequency, so any frequency of vibration could be used to determine velocity for rock materials. However, attentuation is dependent on frequency. Low frequency waves, are quickly damped (seismic waves).

Thus absorption (friction, dumping) and dissipation are responsible for this loss of intensity. The loss of elastic energy in the rock is related to the friction between the vibrating particles and heat transformation and to dissipation related to inhomogenities (fractures, pores).

The amplitude of waves involved in such unelastic is related exponentially to the distance the wave has travelled (Appendix C).

The absorption coefficient of elastic waves depends on the properties of the rock (elastic, thermal and internal friction) and on the frequency of the vibrations.

Experimental data on absorption of elastic waves in rocks show a linear dependence on frequency as opposed to quadratic in metals and other materials (Appendix C). In clay rocks absorption is proportional to the logarithm of frequency. There is evidence that absorption in rocks is mainly due to diffusive dissipation. The acoustic absorption coefficient is always greatest in rocks in which the velocity is the least.

The monitoring of MA is also effected by the capacity of rocks to reflect and refract elastic waves. The factors governing these properties are known as specific acoustic impedance which is a ratio of wave pressure to the velocity of vibrating particles (Appendix C). Often the acoustic impedance is expressed as the product of density and velocity.

Reflection and refraction takes place either at the interface between rocks of different acoustic properties or when waves pass into (or out) rock from an external medium. As a first approximation laws of geometrical optics are applied.

Some important acoustic properties of rocks and minerals are described in Appendix D.

Most of the acoustic properties in rocks depend on elastic characteristics. Velocity of longitudinal waves increase as Young's modulus and Poisson's ratio increases (up to 45%). The maximum velocity in gabbro or basalt will not exceed 6000 to 7000 m/sec. Velocity is also influenced by the grain size of the rock (it is generally greater in fine-grained rocks than in coarse-grained rocks).

Theoretical aspects of the acoustic properties in rock is are considered in subsequent paragraphs.

2.4. POSSIBILITIES OF MA MONITORING

Selection of proper instrumentation to monitor seismic emissions is related to the expected range of frequency. It is difficult to have instrumentation which covers a broad range of frequency and detects all emissions caused by fracture and micro-cracking. Most microseismic events have low levels of energy release. Figure 7 shows the range of frequency connected with AE and MS emissions. Energy release is that part of the (stored) strain

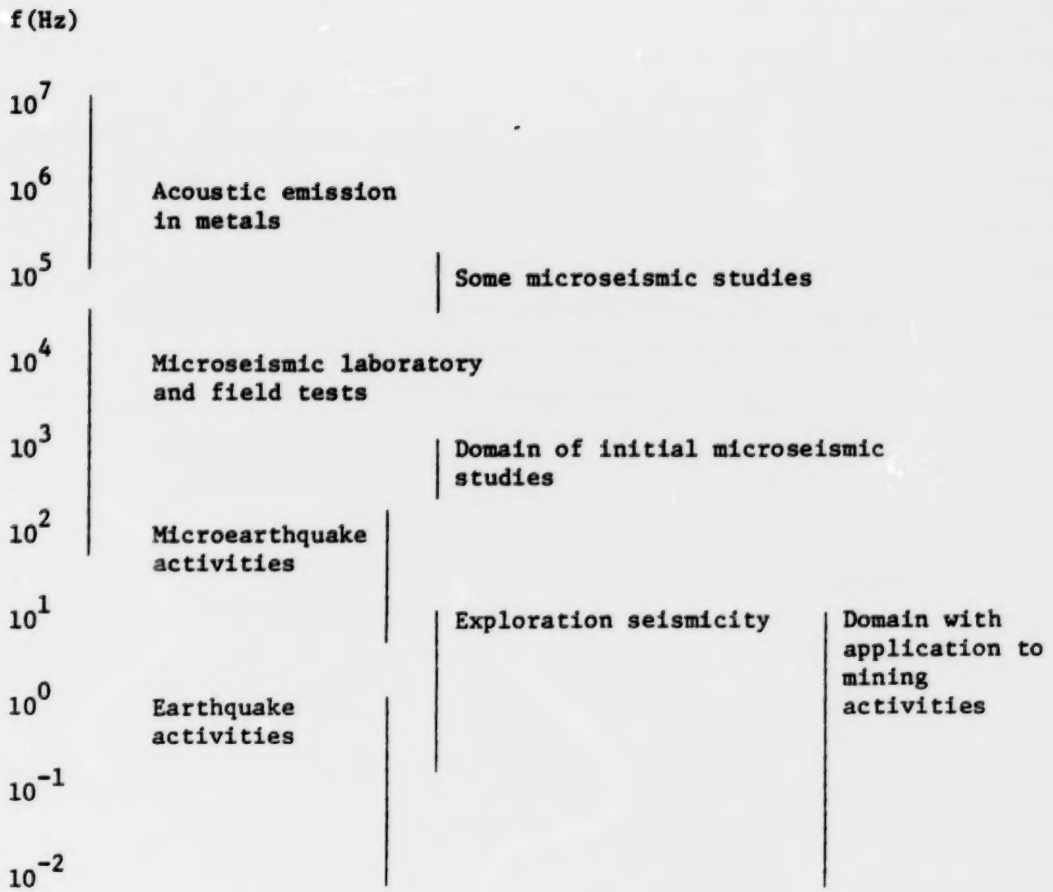


Fig. 7 - Microseismic and seismic frequency ranges (f), and area of applications (37)

strain energy of the body that is released by a given crack propagation event. Much of this energy is consumed non-elastically, for example by the crack propagation process is the rock is pliable. The stored strain energy available for release if a static elastic energy; that portion converted to waves becoming dynamic elastic energy. Microseismic monitoring to wave become dynamic elastic energy. Microseismic monitoring thus yields information about the elastic state of the rock only. It is difficult to evaluate the state of a particular rock only by monitoring the seismic energy release which is only a part of the balance of energy involved in the failure. Generally it should be recognized that the relationship between the component of deformation, and the correspondent energetical expression of deformation is not fully known. This relationship allows the utilization of microseismic measurements to evaluate the process of failure.

The types of MA monitoring focusing on such problems are:

- Measurement of the Accumulated Energy or the Total Energy. These types of measurements give indications on the sum of the energy released during a specific time interval. Several other energy related parameters may be considered such as the energy per event and energy release rates.
- Measurement of the AE or MA Energy. Several methods which determine the magnitude of the events are available.

Utilization of the energy approach on rock failure requires knowledge of the specifics of waveform emissions; mainly the peak amplitude and a complete evaluation of the duration of the events. The duration is generally well assessed by the actual routine of AE measurements which monitor event rates (the number of events per unit of time) or accumulated activity by detecting the number of events during a specific time interval. It should be underlined that most of the actual measurements are only focused on microseismic rates or on accumulated activity. Very seldom are the amplitude of emission measurements made. Seismological application gives an estimation of energy. Table 1 summarizes the types of measurements and data from the different monitoring avenues.

Great variations in energy and frequency of emission can be expected depending on the volume of rock and the mechanism of failure. A typical micro-seismic emission indicates that individual events are made up of a wide

Table 1 - Summary of measurements to monitor AE and MA

Type of measurements	Parameters derived
1. Number of events	- rate of emission - accumulated activity
2. Microseismic amplitude	- maximum amplitude of event
3. Microseismic energy	- magnitude - total released energy - energy release rate - energy per event

range of frequency components. The usual field tests refer to frequency ranges between 0 and 5000 Hz. Frequency over 5000 Hz to 10 000 are present but increased travel time or distance alters the detection of high frequency components.

The volume and the properties of rocks (mainly brittleness) relates to the release of stored stress energy. Energy released can vary from the strong events felt over large areas to the very small events which are detected only by sensitive geophysical instrumentation. In general, the larger the event the lower the frequency. For all events most of the energy is contained in the lower frequency components of the microseismic wave. Most of the energy associated with microseismic modification of mine geometry is expected to be in the shear portion of waves.

2.5. GEOMECHANICAL INTERPRETATION OF MICROSEISMIC EMISSIONS

Mining activity alters the stress equilibrium of the surrounding rock thereby triggering undesirable failure. The process of failure is always associated with the release of energy. Microseismic monitoring is based on the principle that rock failure is preceded by gradual micro-scale energy emissions and early detection of these emissions can be used to locate any build up of critical stress. The emission of energy is divided into two groups: seismic or microseismic. The two are differentiated from each other by the size of the energy emission. Large energy emissions are measured on the Richter Scale. Microseismic activities are low energy level emissions and are measured in terms of the frequency (number count) of the released energy.

The physical significance of both emissions is the same and is related to the intensity of the fracture development.

To utilize microseismic measurements as an early warning of rock failure, the interpretation of the physical meaning of such energy release is useful. An easy interpretation can be made using the Richter approach in defining the energy release associated with the seismic activities.

Without going into the details of rock properties, fractures associated with seismic phenomena may be expressed:

$$OF = 10^{m-3} \text{ (in mm)} \qquad (1)$$

in which OF represents the induced offset of a failure fracture of 1 km in length and m represents the strength or the magnitude of a seismic event on the Richter Scale. Fractures of 1 cm corresponds to a magnitude of four events, 1 mm to a magnitude of three events, 0.01 mm to a magnitude of one event.

Qualitative interpretation of the intensity of the fracture development from seismic data may not be fully applicable to a lower range of energy emissions. In this case, it is essential that the nature of the material be taken into consideration. Although the actual interpretation of fracture intensity is related to seismic data, it should be used only as a reference to evaluate the order of magnitude of the induced fracturation. Using data on fracturation the energy emission associated with fracture development may be evaluated from the same approximation (Formula 1),
$M = 3 + \log OF$.

Certainly such seismic energy emission assessment does not relate to the energy release of particular events. The energy is a value of total energy release which may occur in several patterns. This assessment is valuable if the release is a singular event (which is seldom the case) and is of little use for early warnings of the events. If the release consists of uniform energy emissions, such as the microseismic activity, a general frequency of emission can be estimated. Because of the unknown manner of the pattern of energy release, identification of a failure mode is important. Eventually if the failure mode is estimated, which is often possible, simple rock mechanics in laboratory testing can supplement the expected pattern of

information on the energy release. As an example, 150 events were located in a slope close to the area of an observational bench and a significant crack developed (37). Using only two-dimensional information on the crack opening (4 m in length with an offset of about 50 cm) and without specific data on the rock properties, the total energy release was evaluated in term of seismological significance.

The fracture in the slope indicates a seismic emission with a total energy emission of about 3.3 magnitude.

It should be mentioned in reference to this evaluation that the total energy emission can be released in several unknown patterns. An evaluation can be made by monitoring 150 events in an unstable area and by further estimating the energy per event. Such interpretations and knowledge of the fracture mechanism is critical in developing a reliable, early warning procedure, for any microseismic monitoring of underground or open pit operations.

2.6. MICROSEISMICITY AS AN ASSOCIATED PHENOMENON IN ENGINEERING PROJECTS

Most of the microseismic energy released in fracturation is elastic energy (as in an overstressed spring) and the frequency of these emissions are significant.

The relationship between mining and mass rock movement is well known in both underground and surface mining. Miners know that underground rock "talks" and "bumps" in response to stress changes induced by mining. It has been established that seismic events induced by mining activity radiate energy of a magnitude ranging from microseismic motions to large bumps and rockbursts corresponding to a seismic magnitude of five on the Richter Scale.

Seismic activity has been studied in gold mines (38), in coal mines (39) and in potash mines (40). No definite conclusions on the effect of rock properties (whether brittle or ductile) can be drawn. Rock failure in regions of maximum stress concentration, near the edges of these excavations, depend on the nature of the mining activity. The location of seismic events is found to occur within tens of meters of the advancing faces.

Microseismic detection technology has no doubt contributed to safety and ground control, Hardy (1972,1975). It is, however, quite difficult to separate natural earthquakes from man-induced earthquakes near active mining areas. The problem is that many mines are often located in seismic regions and blasting is always associated with mining.

Even with these limitations, some well-documented cases have been recorded. Direct relationships between tremors in gold mines in Johannesburg South Africa and gold mining was established and the location of the tremors were closely identified with the location of active mining (41). Tremors with a magnitude between 2 to 4.1 were recorded Witwaterstand gold mines (42). The gold bearing strata of a thickness of about one meter was extracted almost completely over an area of many square kilometers.

Earth tremors have affected North Staffordshire (U.K.) since the last century where coal extraction has been extensive. Several intensive tremors estimated to be of a magnitude of 3.4 affected an area of about four square kilometers. Here a clear relationship between the earth tremors and mining was established. The series of earth tremors was caused by the mining of seams at a depth of nearly one kilometer.

Seismic events related to mining activities in Canada have been reviewed by W.G. Milne and M.J. Berry at the First International Symposium on Induced Seismicity held in Banff in 1975 (43). Other examples, such as events with a magnitude of 3.9 on the Richter Scale, at Malartic Mine in Quebec (1975) are also known. An occurrence of four earthquakes near Saskatoon (1979-1980), historically a non-seismic region, is connected with potash mining operations. These tremors were of a Richter scale magnitude of between 2.3 and 3.0 and were interpreted to be the result of mining in places where rocks above the mine undergo spasmodical movements. References on more recent seismic activities (1984) are included in Table 2 and publications such as Davidge, 1984 (44), and others, were presented at the recent symposium (3). Mining practices have changed and this may indirectly change the frequency of seismic activities. The triggering conditions and the seismicity itself is controlled by stress concentrations. Improvement of ground control may be the simplest way to avoid the undesirable earth tremors.

In open pit operations seismic activity is related to blasting and slope instability. Even though cases of man-made seismicities are known, the hazards are not considered to be extreme (45).

Significant microseismic and seismic activity is known to take place in hard rock mines in Ontario. The most significant mode of improving use of the monitoring technology is the early warning through the detection of signals, their frequency and location of the source.

Table 2 - Microseismic Monitoring Mines

Location	Mineral	Activity*	Instrumentation	Observation
Star Mine, Hecla, USA	lead-zinc, silver	2.6	24 channel	30% successful prediction
East Malartic,Can	gold		16 channel	observations before mine closure
Western Mine S.Af.	gold	1.5-2.5	4 tridimensional monitors,	3000m depth
Shortland, Aust.	coal		4 detectors	accelerometers
Mid Continental, USA	coal		multi channels	frequency response, 10-110 Khz
Cynheidre Coll, UK	coal		single channel	accelerometers & geophones
Akabira Mine, Japan	coal		2 channel	for advance boring
Minami-Obyubari, Japan	coal		2 channel	for advance boring
Blyvoorritzicht, S.Af.	gold		30 geophones	depth up to 3800m
Uppsala, Sweden	iron	max 3.2	-	3 dimensional
Mount Isa-Aust.	copper, lead-zinc		32 channels	array, cut and fill stopping
Szombierki, Poland	coal		4 & 7 channels	longwall and hydraulic backfill
Ruhr, W.Germany	coal		12 geophones	measurements related to destressing
Westcliff Coll. Aust.	coal		single channel	depth 200m
Henderson Mine, Col. USA	Molybden		7 geophones	block caving method
Kleofas, Poland	coal		stationary multi ch. or portable single ch.	-
Flaconbridge, Ont.	nickel-copper	3.2-3.5	32 ch., 25 OMP monitor	900-1800m depth, cut & fill
Wawa, Ont.	siderite, iron ore		1 ch., McPhar	inconclusive test
Campbell Mine, Ont.	gold		32 ch., Electrolab	pillar stability
Geco Mine, N.B.	-		1 ch., McPhar	-
Chadbourne, Quebec	-		1 ch., McPhar	inconclusive test
Brunswick No. 12, N.B.	zinc-lead, copper		1 ch., McPhar	cut and fill
Gaspe Mine	copper		1 ch., McPhar	information on scaling
Creighton Mine, Ont.	nickel	4.0	16 ch., Electrolab	shear slippage shaft No. 5 3200-3800 level
Potash Corp. Sask.	potash	2-1	1 ch McPhar	mine induced seismicity

*maximum magnitude on Richter Scale

The earth is a permanent source of microseismic activity. Sources may be related to industrial activities of all kind. Microseismic monitoring of large dams form the basis of most microseismicity studies required to identify the supplementary induced activity in an industrial undertaking.

In analyzing the variation of emissions, it is assumed that there is increased microseismicity with increasing energy release. This concept is not new and research into the prediction of larger seismic activities, such as earthquakes, is in progress. Investigation of Reservoir Induced Seismicity (RIS) is a well established field.

Historically, impoundment of large reservoirs near hydro power plants represents the first type of engineering activity which significantly alters the stress in the local state of the rock. The stress change in such reservoirs,sometimes is related to RIS in about sixty water storage facilities. The highest magnitude of any man-made activity recorded on the Richter Scale was 6.5 at the Koyna dam in India. From an analyses of stress development, at any specific site, it is possible to identify the factors leading to such triggering and it is possible to predict potential seismic events (17,36).

A review of experience in other engineering fields is useful in framing mining safety measures to control seismic activity. The evaluation of triggering mechanisms in mining could be rendered more precise through the identification of stress conditions in mines having similar rock burst problems. Other man-made seismic activity can also be reviewed for the purposes of evaluating critical threshold conditions.

Audible warnings of five to ten seconds prior to failure, have been reported in the vicinity of mine outbursts. The typical time lag of audible warning is insufficient for any effective safety measures. Detection of higher frequency noises developing from small cracks has been suggested to be an alternative to extend the warning time (Fig. 5)(124). Field observations suggest that the warning time might be increased to at least fifteen seconds prior to failure.

3. MICROSEISMIC MONITORING FOR MINING APPLICATIONS

3.1. OVERVIEW OF PRACTICE

The area of microseismic monitoring is dominated by significant undertakings related to field measurements. Analysis of the practice of microseismic measurement as indicated by the first three conferences on AE/ME in Geological Structures and Materials (Fig. 8) refer to direct field measurements as the main avenue of microseismic applications. The fourth conference will be held in October 1985 and preliminary presentations are referenced in Appendix E. The field measurements are focused on several areas that are mainly connected with underground mining, coal, hard and soft or ductile rocks. Specific emphasis is related to outburst monitoring and prediction. Few attempts are related to open cast operations. An increase of utilization is seen in the diversifiation of applications, such as, gas storage reservoirs, hydrofracturing, fluid storage in geological materials and foundations of dams.

Field measurements encounter a substantial number of unknown variables which rarely could be defined during most of the mining operations. Sometimes, the results are not fully rewarding and laboratory investigations try to supplement the missing elements in a controlled environment. More often field undertakings are complemented by laboratory investigation, prior to or parallel with field trials.

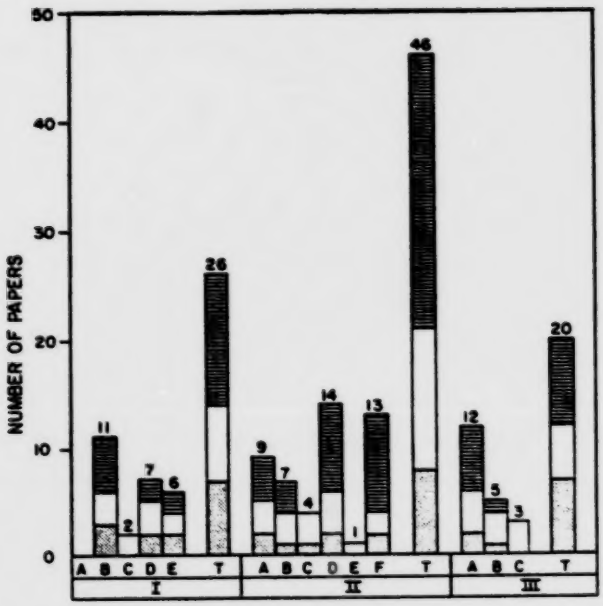
3.2. UNDERGROUND MINING

3.2.1. Hard Rock Mining

Extensive testing with AE equipment began in Sweden (1956) when the investigations of the United States Bureau of Mines and some Russian developments became known.

Measurements of acoustic emission (AE) in rock was introduced in the late fifties. It was welcomed by the mining industry as a promising approach to the indication of pending rock falls or other instabilities of rock masses. It was accepted that microseismics indicate the condition that the load acting on the rock mass approaches its load bearing capacity even though neither of the quantities involved is known.

The need for a suitable warning system based on objective measurements is even greater today than it was twenty years ago. Due to the



DEVELOPMENT TRENDS IN MICROSEISMIC MONITORING

- as refered by first three conferences (total - 112 papers)

1975 - 25 papers
1978 - 41 papers
1981 - 46 papers

I - laboratory
II - field tests
III - instrumentation
Areas: A,B,C,D,E,F;

Fig.8 - Research developments as referred by the three conferences on microseismic activity

Total 92 papers

First 1975	Second 1978	Third 1981
I Laboratory	II Field tests	III Instrumentation

IA - Energy emission
IB - Application to mining
IC - Outburst
ID - Other indirectly related to mining

IIA - Underground coal
IIB - Underground soft and ductile materials
IIC - Underground hard rock
IID - Outburst
IIE - Surface Mining
IIF - Other application as gas etc.

IIIA - Hardware development
IIIB - Software development
IIIC - Analytical analysis

IE - Other areas
IT - No. of papers
IT = IIT = IIIT

mechanization of mining operations, the miner has lost, to a large degree, his direct contact with the rock mass and his ability to survey and control the condition of the rock in his working area. Admittedly the miner is better protected against the fall of smaller rocks (weighing 100 kg) by being placed under the roof of a drilling jumbo away from the face; however when considering the fall of larger rock masses, the miner's safety has not been improved by mechanization.

Considering the economic aspects, mechanization implies that mining operations have become highly sensitive to disturbances, including those due to rock falls. This is caused partly to difficulties in maintaining production from highly mechanized working places and partly due to the high capital costs associated with heavy equipment. Conclusions reached on extensive measurements collected at Boliden Mines (123) identify reliable AE measurements. Rock source location techniques assist in this respect.

Even though the physical nature of MA has been explored extensively in recent years, the acquired knowledge appears to be insufficient. The aspects of the physical nature which should be identified are:

- the characteristics of MA pulses (e.g. duration, spectral energy, and distribution);
- the change in these characteristics due to the transmission of waves through rock; and
- the time of MA generation in advance of failure.

The high stress stope surroundings in deep level mining causes the the rock to fracture. Unless the mechanism of fracture is understood mining methods cannot be improved. There are two important aspects to consider in regards to rock bursts or violent movement. Falls from the hanging walls should he avoided, and secondly, the rock at the face should always be sufficiently fractured to facilitate the method of mining.

Seismic research has played an important role in South African (322) gold mines in helping to identify the causes of unstable rock movement and the means to control (within limits) the undesirable rock bursts. It has been found that large seismic events, with a magnitude greater than 3 on the Richter Scale, are associated with large geological faults. However, there are smaller seismic events, in the range of -1 to 2, which occur in deep level mining in the region of the stopes. Of these, only a few are of sufficient magnitude to cause damage in a stope.

It is evident that there are many more micro-seismic events which occur very infrequently than there are small seismic events. There is sufficient data to estimate that, in front of a stope panel, being mined every day, 200 m long, and having a typical energy release rate of 20 MJ/m^2, at least 2500 micro-seismic events occur each day, whereas, only one event of a magnitude between -1 and 1 occurs every 5 days. A larger event would probably occur less than four times a year.

Field investigations on the subject of ground subsidence over steeply-dipping underground mines were conducted at abandoned mines in Upper Michigan. At the Sherwood Mine in Iron County, an eight element seismo-acoustic array has been continuously monitoring micro-seismic radiations since the cessation of mining and pumping operations in August, 1978. Sensors and preamplifiers are located in water wells and in underground holes and are connected to a central recorder by shielded cables up to 800 m in length. On going observations suggest an active piping mechanism of subsidence. Major AE/MA anomalies have been observed but emission patterns are complicated by the widespread distribution of sources. The interpretation of microseismic data is supplemented by geophysical, engineering and hydrological measurements.

Evidence is obtained to support piping as an active mechanism of subsidence in the Sherwood Mine vicinity. The Sherwood Mine represents (329) a very complex field model which complicates the interpretation of measured parameters. Many sources of acoustic emissions are operating concurrently and are distributed in such a way that the signal paths and direction of arrivals are diffused. Acoustic emissions can be correlated with processes that relate to the stability of soft rocks and to impending failure. However, in contrast to applications of MA in studies of isotropic media with concentrated sources, it is critically necessary in this and similar field situations to have other sources of information in the analysis. The study supports the contribution of microgravity and electrical methods of geophysics as well as engineering and hydrological measurements in the interpretation of a physical model of subsidence over steeply-dipping mines and in the analysis of acoustic emission.

3.2.2. Rockbursting in Hard Rock Mines

Research work in the early forties using microseismic monitoring to predict rockburst occurrence resulted in negative conclusions. However, the equipment used was rudimentary as compared to the sophisticated electronics available today.

The costs of various microseismic monitoring systems are significant as compared to more conventional instrumentation but are insignificant when compared to the cost of damage due to rockburst occurrences. The method requires long term commitment and specially trained individuals to maintain it

At present, there are limitations in analyzing the data received which must be overcome before the method is to be used routinely as a rockburst prediction tool. However, it can be profitable to use as an indicator of anomalous areas which are then further evaluated using more conventional techniques. This strength alone makes microseismic monitoring an important tool to any mining company having serious rock bursting problems.

Several seismic monitoring networks are installed around the world. As an example (3224), a seismic network was installed at the Blyvooruitzicht Gold Mine near Carletonville, South Africa, during 1979, to study rockburst activity at the mine. Signals from up to 30 geophones across 5 km of mine workings were transmitted by cable to a site on surface and digitized at 1000 samples per second for each channel and data for seismic events were recorded on disk. Seismic events were located using P and S-wave arrival times selected from seismograms displayed on a graphics screen. The total rock deformation was in good agreement with the sum of the seismic events and a relationship exists with the modulus of rigidity, and the volumetric closure of the stopes expected from elastic behaviour of the rock mass. A net increase in seismic activity was caused by extensive dykes or faults.

The fairly constant slope of the saw-tooth curves representing seismic activity suggests that seismic events occur after the build-up of strain energy caused by a certain level of mining. A careful analysis of this data might provide predictive information over a time scale of one week. A suggestive rock source location from the Galena Mine, in the United States is given in Fig. 9.

More recent examples could be given in relation to the practice in hard rock mines in Canada. As a general reference, a workshop organized by

CANMET in Sudbury Ontario in 1984 offered a good opportunity to compare the efficiency of the actual state of burst monitoring. A future CANMET report will assemble the presentations which make a good review of the Canadian experience (3). Falconbridge has a history of a significant microseismic monitoring system which has been operating in the area around the No. 9 shaft hoist room located 25 m from the ore zone at a depth of 1200 m (Fig. 10). Several wide faults dissect this area and have been shown to be microseismic active due to mining. Even with the extensive microseismic instrumentation and a good interface with computer support, the early warning of rock bursts was not yet been fully achieved. The precursory early warning is related to preliminary mechanisms or potential hazardous pattern identification. The identification of the potential mechanism of instabilities is related to each geological structure and in the case of rockburst activity at Falconbridge (June 20-23, 1984) it is related to the necessity of early identification of the hazardous pattern. Appendix F contains the summary report of the technical committee which analysed this particular situation. It has to be ascertained that some of the mechanisms, such as the slippage along the faults, are difficult to identify. An important conclusion to be drawn is that full understanding of the the geological environment is part of any successful microseismic monitoring.

3.2.3. Soft Rock Mining

Microseismic activity in salt rocks, the most common being potash, deals with phenomena in the transition zone from sound to ultrasonics. The energy release in salt materials is released for different reasons than in hard (brittle) rocks where fault-ship and fracture development are the controlling mechanism.

Some microseismic emission patterns in salt material are similar to phenomena in hard brittle rock; e.g. the frictional sliding along fracture planes, or the development of cracks, or the growing of cracks and faultline events. The creep of evaporites involves mechanisms such as crystalographic dislocation and mineralogical phase change produces different patterns of acoustic emission. German studies (2211) report successful monitoring of emission from phenomena such as the formation of sink-holes above a mining area (Fig. 11a) and variations in the water level (Fig. 11b).

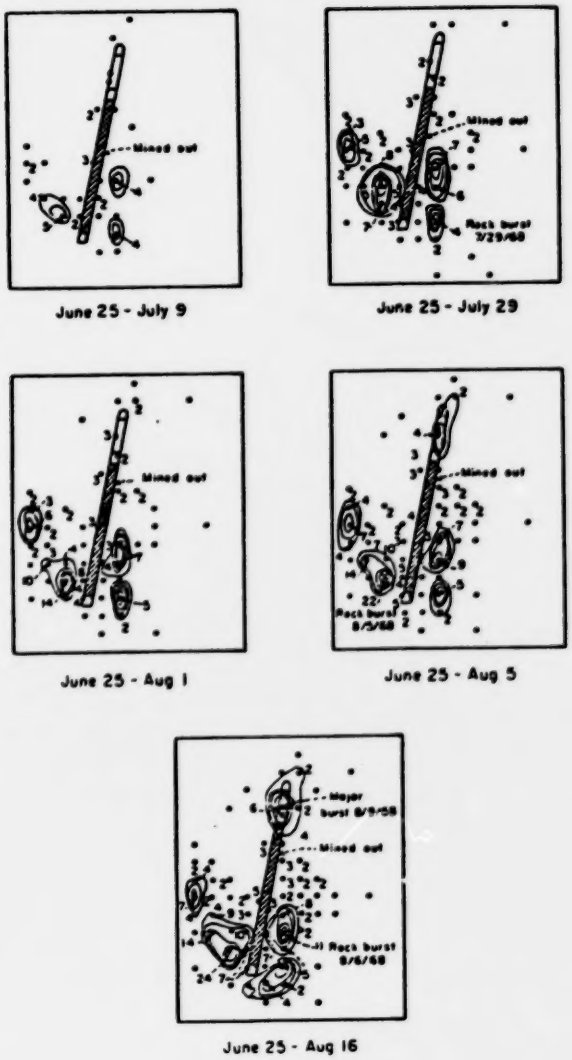


Fig. 9 - Cumulative plots of rock noise source locations - Galena Mine, 34-76W stope 1968 (53)

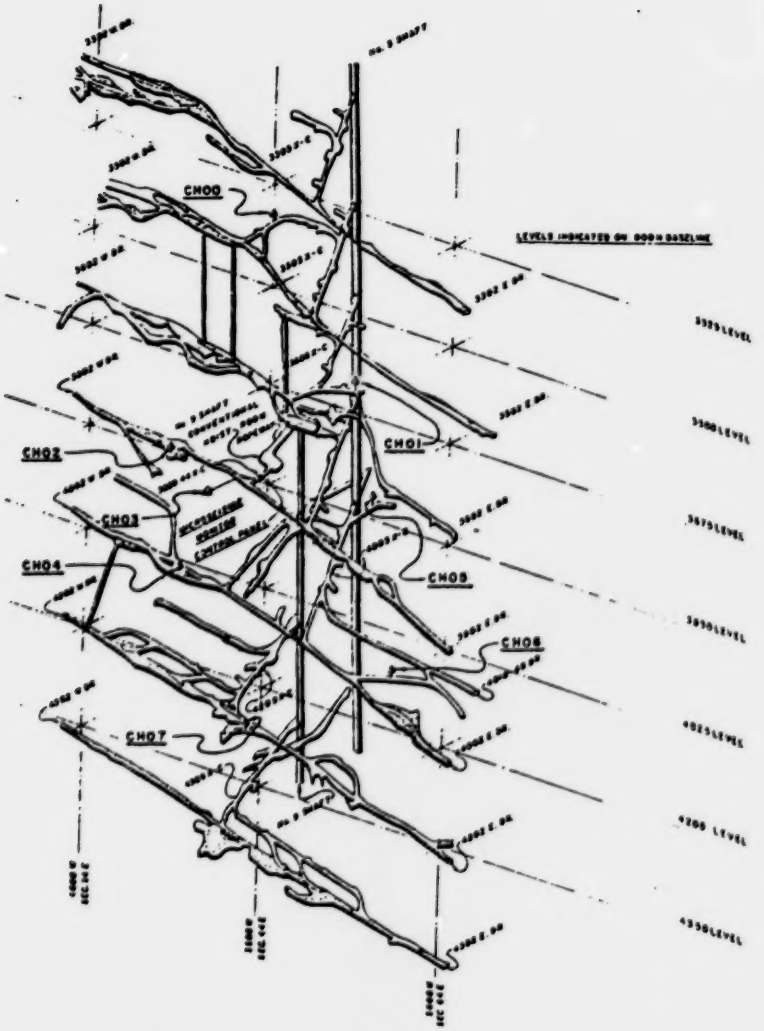
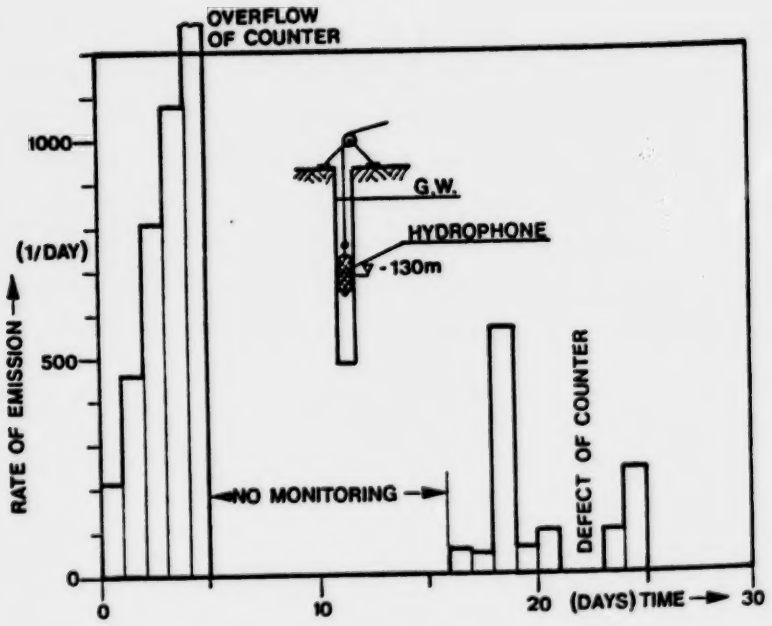
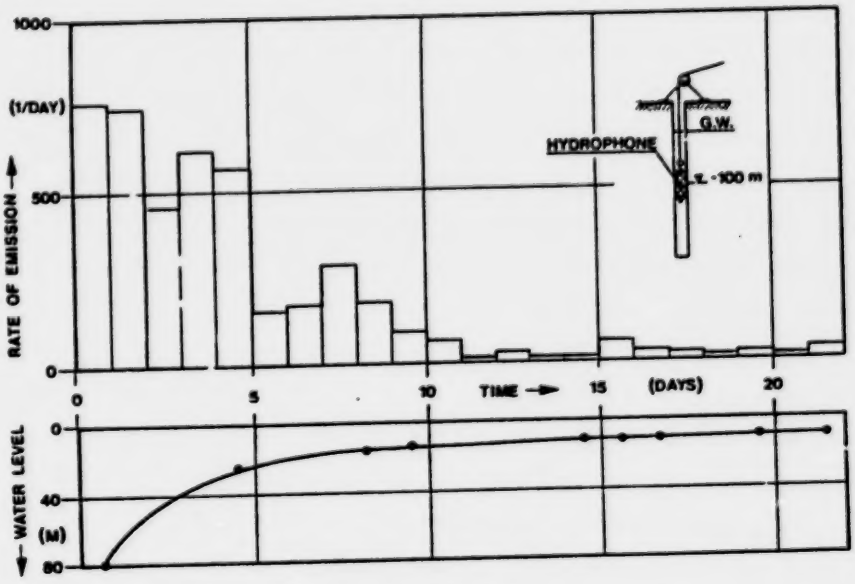


Fig. 10 - Microseismic monitoring in a deep hard rock mine (16)



(a) Rate of acoustic emission during formation of a sink-hole



(b) Rate of acoustic emission and rising of the groundwater level

Fig. 11 - Acoustic emission related to salt rock mining (2211)

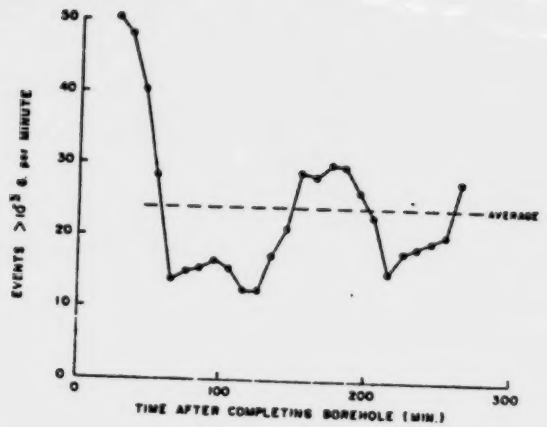
Field studies have been made into the stability of potash pillars the entries of mined-out panels (8). Microseismic emission count rates correlate quite well with the mean stress in pillars (Fig. 12). Stress evaluation was obtained by independent stress meter measurement. Similar good results were obtained in potash by high frequency microseismic monitoring using RM1 Rock Monitor at the Cory mine. These studies indicated modifications in the event count in response to mining activity (Fig. 12a), as did an underground experiment done at the PCS Mining Lanigan Division referred at the Sudbury 1984 workshop (Fig. 13).

Extensive salt research has been done to get a more thorough knowledge of the creep mechanism. Microseismic emission tests on small cylindrical samples (ϕ=10 cm by h=25 cm) indicate that after 122 days of loading, the sample still produced significant emission activity (Fig. 13). Analysis of the nature of the signals indicate an exponentially decaying shape (2211). In regards to duration, signals up to 180 m sec were observed with a maximum well marked check on the interval between 20 and 40 ms for about fifty percent of the signals.

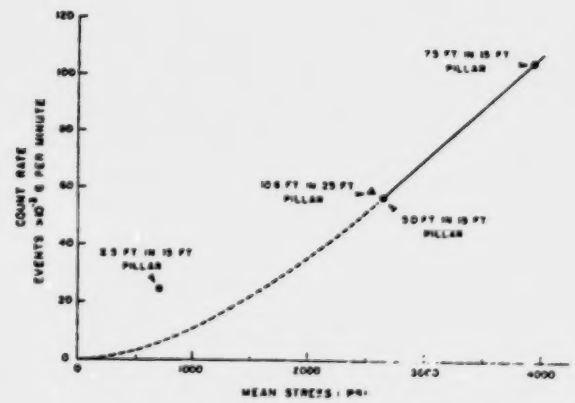
When considering measurements over a one year period, the relationship between pillar deformation and time is linear. Pillar deformation occurs by a creep process that proceeds with a constant creep velocity (327). During the same time period, the microseismic emission rate is characterized by a number of distinct variations with relatively minor significance.

In contrast to the event rate, the "b" values which control the frequency of amplitudes remain constant. The "b" values are considered to be a function of the modification of stress conditions of rock. Relatively constant b values may occur only in small changes in the pillar stress. The "b" values represent the relationship between the cumulative frequency (N) of magnitudes of emissions and the magnitude of the emission (M) and a and b are empirical parameters which indicate a general linear relationship log N = a-bM. Even the clear linear relationship is evident (Fig. 15), when considering the very small values of b, between 0.07 and 0.11, which indicate that the particular nature of emissions are well below the natural emissions. For most mining activities the stress induced emissions have b values larger than 0.9 whilethe natural emissions have smaller (17) values.

It should be underlined that there is very little attenuation of seismic energy in salt, about 1.6dB/m, compared to the relatively large

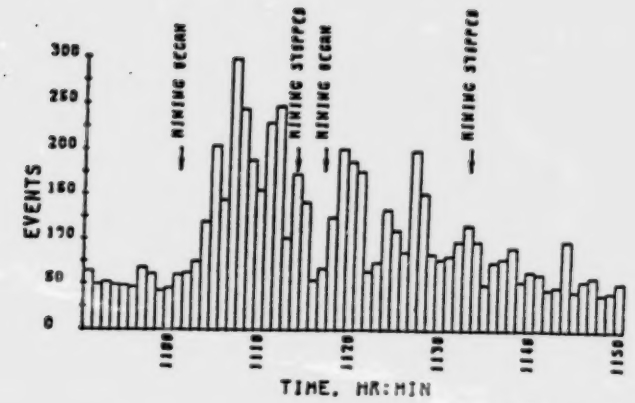


(a) Rate of microseismic emission in a 7.5 m pillar

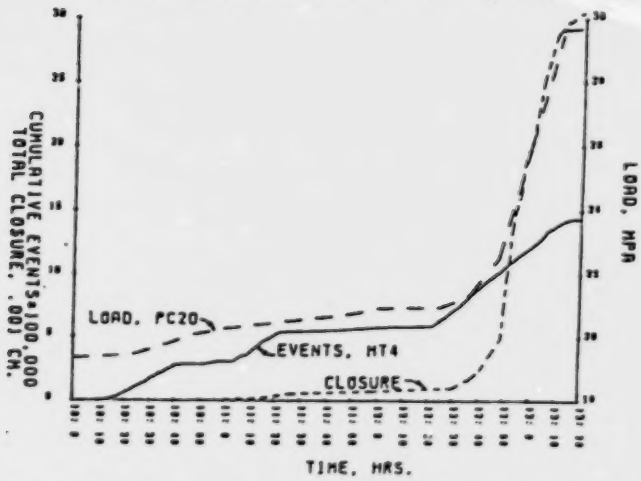


(b) Microseismic count rate as a function of mean stress

Fig. 12 - Microseismic monitoring in Potash mine. King (1976)



Cory Mine Data, Events vs Time (After Vance, 1983)



Load, Total Closure, and Events vs Time, Lanigan Mine, Feb. 13, 1984
(After Mottahed & Vance, 1984).

Fig. 13 - High frequency microseismic monitoring in Potash mine (16)

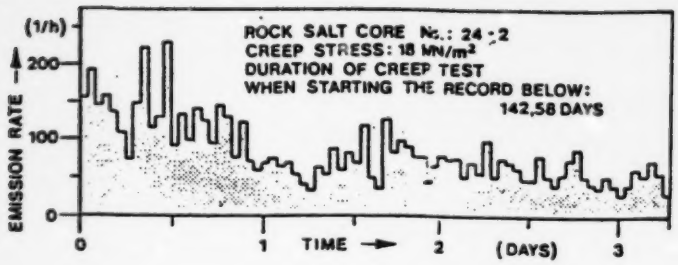


Fig. 14 - Rate of microseismic emission during creep deformation (2211)

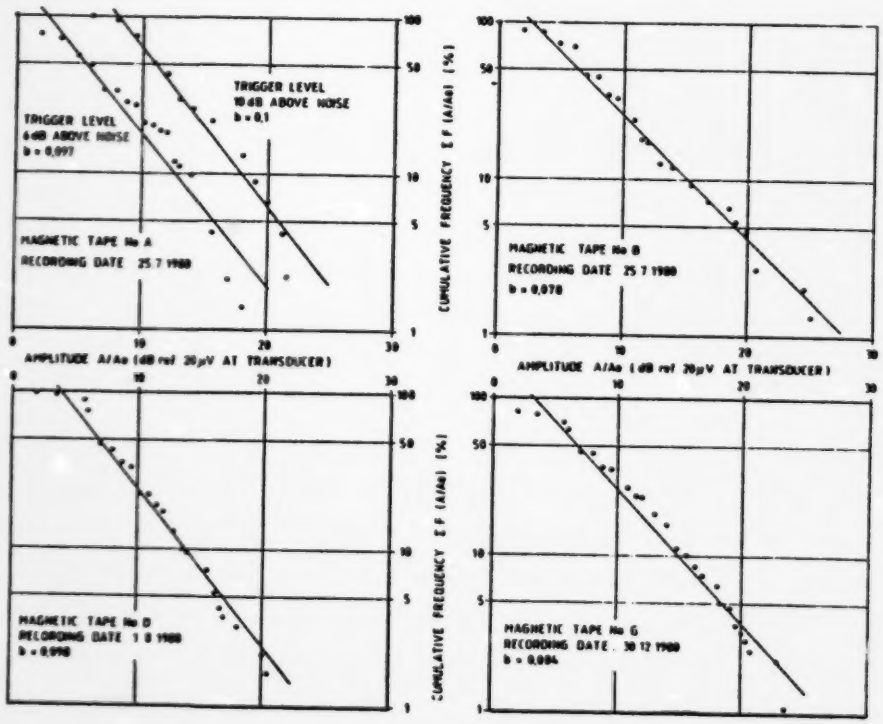

TRIGGER LEVEL
6 dB ABOVE NOISE
b = 0,097
TRIGGER LEVEL
10 dB ABOVE NOISE
b = 0,1
MAGNETIC TAPE No A
RECORDING DATE 25 7 1980
MAGNETIC TAPE No B
RECORDING DATE 25 7 1980
b = 0,078
MAGNETIC TAPE No D
RECORDING DATE 1 8 1980
b = 0,098
MAGNETIC TAPE No G
RECORDING DATE 30 12 1980
b = 0,084
CUMULATIVE FREQUENCY E F (A/Ao) (%)
AMPLITUDE A/Ao (dB ref 20µV AT TRANSDUCER)

Fig. 15 - Cumulative frequencies of maximum MA amplitudes versus amplitude (327)

frequency window for receiving such signals. The signals are discrete pulse and represent a statistical release of energy which is a product of localized events within different parts of the monitored pillar.

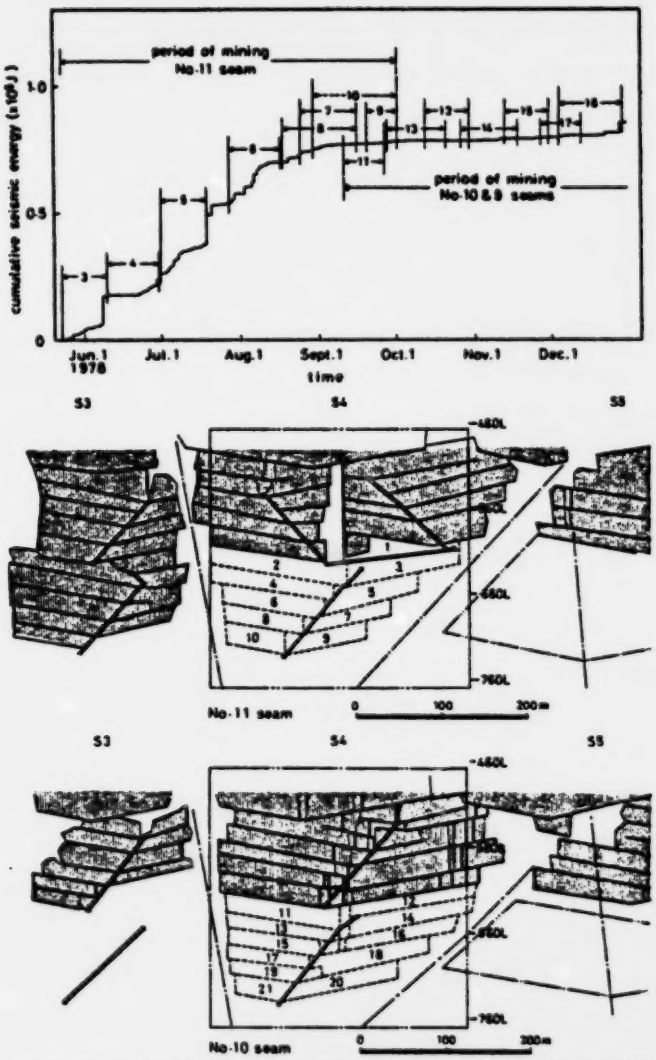
3.2.4. Underground Coal Developments

Mining hazards related to underground coal mining commonly include types of rockbursts and sudden movements. The development of mining operations may require the mitigation of rockbursts hazards. This is discussed in Paragraph 3.2.5.

Winning coal causes the removal of support from the mine structures, which in turn, imposes new load-carrying requirements on the remaining structures. The structure adjusts to its new stress environment and small scale displacements take place. Such constraints are more demanding as new high production methods are developed, such as with longwall mining, and the increase of the stress field with depth. Mining methods are being developed to maintain stability and reduce stress concentrations which are the source of ground instabilities.

Microseismic measurements show a significant correlation between emission and the mining operation, between activity and mine sequences, and between the time rate of events and the approach of the longwall face or changing of activity before and after destressing. In the case of destressing activities, distinction should be made using the differences of frequency, 150-400 Hz for drilling and seismic seam reactions to destressing of 500-2000 Hz frequency (3228).

Microseismic monitoring was applied in Japan (3214) to observe rock failure associated with the hydraulic mining in steeply inclined coal seams with an array which encloses the mining panels. A comparison of activity between, before and after mining of seams showed that the special rate of seismic energy preceding mining was more than seven times higher than that of successive mining. It is important when designing mines to understand which seams have more active microseismicity when mining multiple seams and to identify how much difference is brought about in a quantitative measurement of seismic energy. The reduction of seismic energy seems to depend on factors such as the complex configuration of multiple seams, mechanical properties of rock involved in the bearing formation, and the mine geometry (Fig. 16).



The cummulative seismic energy released from mining panel, since May till December 1978 at the No.1 Pit of Sunagawa Coal Mine. Numbers inserted in the curve correspond to the mining blocks numbers which are indicated in the mine layout on the Nos. 11 and 10 seams.

Fig. 16 - Microseismic observation in a coal mine in Japan (3214)

3.2.5. Rock burst hazard mitigation

Concerns about mining risks, such as rock burst, are complex and include mining design and other stress releasing procedures. This paragraph reviews only the contribution of microseismic monitoring. The concerns related to rock burst are common to all types of formations. However, occurrence is different and is related to the geological setting; both rock type and structure.

Rock bursting is a major hazard in deep mines and the problem becomes more critical as mines become deeper. Loss of production and the expense of clean-up and repair make rock bursting a severe operational problem. Microseismic monitoring of bump or bounce-prone areas in coal mines is very similar to rock burst monitoring. Added operational problems in coal mines are equipment permissibility requirements and the fast-changing mining geometry due to rapid extraction of coal.

The problem of rock burst control resolves into two types of considerations; the first involves factors which effect the incidence of seismic activity; and the second, is concerned with factors which reduce the effects of the damaging seismic events. Geomechanical analysis indicates that the reduction of volumetric convergence offers the best possibility for control of seismic activity by reducing the total potential energy available. All quantities involved in the energy balance are consequently reduced, including the strain energy which is converted directly into kinetic energy at the instant of a rock burst. It should be remembered here that the energy released per unit area mined is a convenient quantitative measurement of the extent to which the total energy is reduced, but it does not refer directly to energy liberated seismically. The energy release rate and the incidence of seismic activity are statistically associated (Fig. 17) but not mechanistically related. Any support method which does not affect the elastic convergence and therefore the energy release rate has only palliative value. It cannot control the incidence of rock bursts but will, at best, reduce the severity of the damage. To reduce the damage is nevertheless an important objective which warrant continued and intensified research.

Rock bursts can occur in geologically undisturbed rock, although they are frequently associated with dykes and faults. The kinetic energy liberated during the event is derived from the strain energy stored around the

geological discontinuity or in the rock mass surrounding the rupture surface that develops in the previously solid rock. It is unlikely that the primitive stress is uniformly distributed throughout the rock mass, even where it is geologically undisturbed. In the vicinity of faults and dykes it is quite likely that strain energy levels are abnormally high even before mining.

Steps taken to minimize the mining-induced energy changes may be sufficient to reduce the incidence of rock bursts to an acceptably low level. These steps may merely involve the geometrical pre-planning of slope layout and an extraction sequence to avoid the formation of high-stress areas, particularly remnants, and so keep the spatial rate of energy release at each working place as close to the overall average as possible. On mines where grade considerations make scattered mining unavoidable and depths are sufficient to present a rock burst hazard, computer analyses should be regularly undertaken. At greater depths and spans where rationalization of mining geometry is not sufficient, it will be necessary to make more drastic changes that will reduce the total energy change as well as the energy release rate.

Where unfavourable geological circumstances prevail, the greatest reduction in energy release rate which is practically attained may not be sufficient to prevent the occurrence of large seismic events which may have been on the verge of happening before any mining took place. It is probable that the magnitude of these events, nevertheless, would be diminished by measures taken to reduce the energy release rate, such as partial extraction. The risk of such events can be minimized only by planning the geometry of the sloping configuration. This implies an understanding of the mechanism of the rupture movement and knowledge of the geological structure of the discontinuity. Obviously monitoring of rockburst and identification of any precursor phenomena is only a part of the mitigation procedures related to hazard reduction of these risks.

The problem of rockburst monitoring is common in both hard and soft rock mining. Some considerations were made in Paragraph 3.2.2 related to hard rock mines. In this paragraph emphasis has to be placed on soft rock mining. Common problems with rockburst monitoring are found and may be considered outside of the peculiarities of the geological environment.

Extensive monitoring of rock burst hazards have been undertaken around the world. Table 2 summarizes some of the most important projects. An

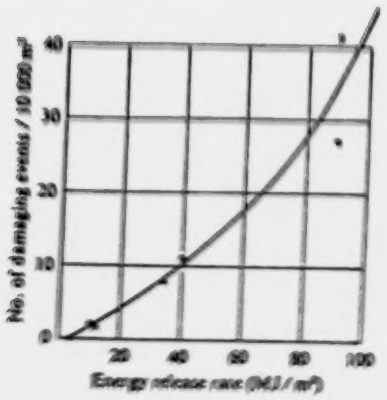


Fig. 17 - The relationship between energy release rate and incidence of rockburst from Rock Mechanics in Mining Practice by S. Budavari 1983, The South African Institute of Mining and Metallurgy Monograph Series No. 2, p. 282.

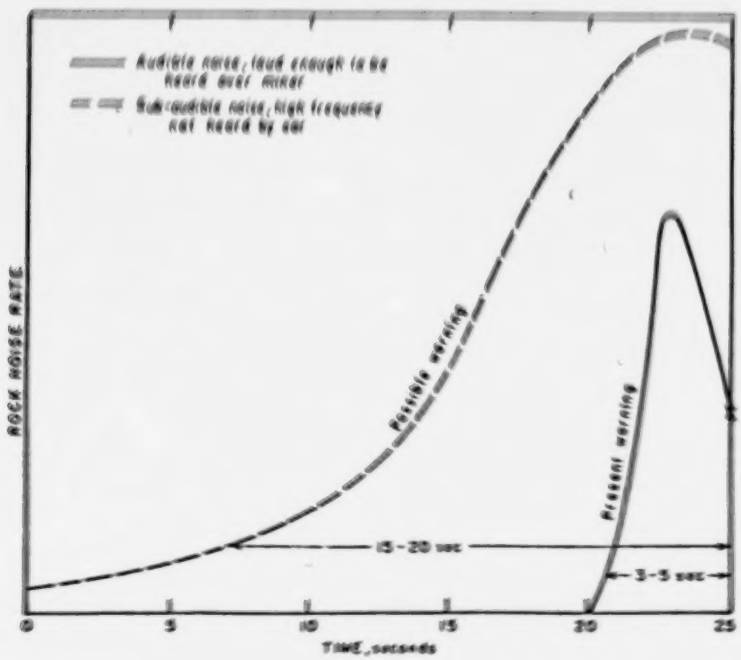


Fig. 18 - Theoretical premise for outburst research. F. Leighton (1981)

important segment of this undertaking is in coal mining. Consideration should be given to the character of the event which is sometimes only of a gassy nature, however, most of the time, it is related to coal and gas. For example, in a recent incident in Japan at the Akabira coal mine, powdered 200 m^3 of coal and 16000 m^3 of methane was ejected instantaneously and three lives were lost. Outbursts may result from less than 1 ton to more than 5,000 tons of coal being forced into an opening and can be accompanied by several thousands of cubic meters of gas release.

Observers of outbursts have reported hearing rock noise in the failure area about five to ten seconds prior to the failure. The typical time lag of audible warning is insufficient to allow personnel in the critical area to protect themselves. Detection of the higher frequency noises from the small crack development in the failure process may provide warning time as indicated by F. Leighton (1981) in Fig. 18. Field tests recorded activity similar to audible emissions and recognized anomalous activity prior to the failure. The energy accumulated during each interval of time (the energy-event ratio) indicate an anomaly that precedes the time of the failure, but only by approximately 15-20 seconds.

Records indicate that the rockburst phenomenon is associated with abnormal stress concentration. Causes of outburst include high abutment or remnant stresses which are present ahead of the face or pre-existent volume of crushed rock (Fig. 19).

There are three methods referenced by Blake et al (1974) for source locations: the General Block Method and two methods related to the P-Wave (a direct solution on the Least Square Method).

With regards to the General Block Method, a unique wave velocity is assumed in the arrival time determination. Reference is made to the important divergence of arrival times, frequently related to the third or fourth geophone. It would appear difficult to suppose eliminating all possibilities of divergence of arrival time at a particular site. Test blasts may allow reduction of divergences.

Five arrival times for a source location is required in the P-Wave Direct Method. At least one more arrival time for a solution is necessary for the Least Square Method utilization and minimizes inaccurate seismic velocities and first arrival seismic-wave picks. No residual or error values can be calculated for the first two detectors. Typical microseismic signals

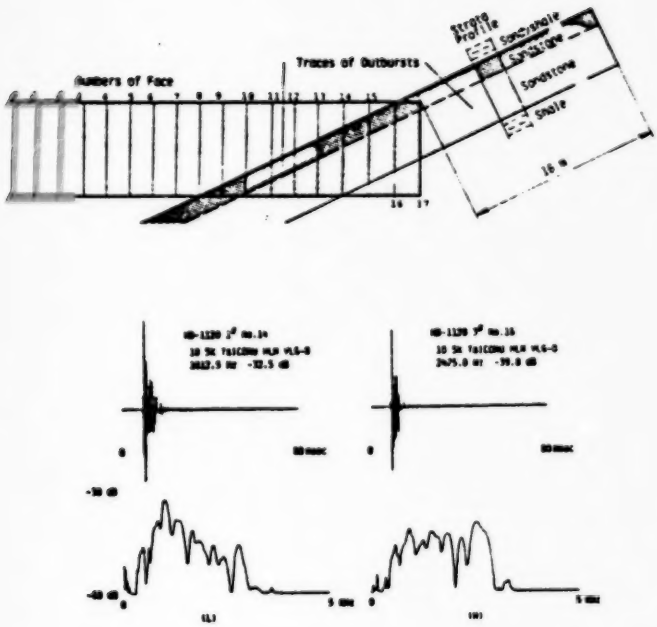


Fig. 19 - Interpretation of microseismic signals. Signals from outburst-prone sandstone seam and associated frequency spectra (3227)

which were recorded through the band-pass filter of 300-5000 Hz and the frequency spectra from the Akabira Coal Mine (Japan) are presented. The level of background noises is negligibly low in comparison with that of the signals as shown in Fig. 19. Many of the signals detected, indicate a frequency of about 2600 Hz with some difference between the two spectra considered to be the difference in the coupling of the transducers to the rock.

At this stage, the microseismic monitoring should be considered in parallel with other outburst prediction techniques such as PO/60 Ratio for gas emission, time-related gas emission constants, total gas content of coal, electrical conductivity of coal, and volume of cuttings produced by a standard borehole ahead of face. Detection of microseismic precursors should be considered site and material specific. Such approach allows identification of geological pattern on which bursts are preceded for some hours by an increase rate of acoustic emissions and a special concentration of micro-events in the zone of eventual failure. Several successful examples could be given (Fig. 5).

Readily recognizable microseismic and percursor phenomena do not precede all rock bursts, thus making accurate prediction of the time of occurrence not reliable enough.

3.3. SURFACE MINING

Increased productivity in large open pit operations is related to maintaining good stripping ratios. In complex geological structures for open pit operations the maintenance of high stripping ratios is related to the condition of the stability of the slopes. The maintenance of slope stability has an impact both on the economical input of each particular pit and on the risks related to production in quite hazardous conditions. Hazards related to pit slopes is usually related to complex geological structures. Risks are connected to hazards for man and equipment, both of which, operate at the toe of unstable slopes. Risks are related to the whole economic output of each particular pit. Slope instabilities and failures develop as pits become deeper because there is more loose coal. It should be underlined that loss of coal at the bottom of the pit affects mainly the reserves which have the best economical conditions related to the stripping ratio. If the lost reserve is important the whole coal output from the particular pit could be significantly affected.

Complex geological conditions, as well as the exposure of man and equipment to high risks, are reasons why coal operations in the Rocky Mountains should address the problem of mitigation of hazards related to slope instability. Concerns related to safe design of slopes are addressed with an awareness to avoid overdesign of slopes. Overdesigned slopes significantly increase the stripping ratios. This necessitates that slope design be made as near as possible to the limits of engineering and with safety factor close to the equilibrium limit value of one. Slope instabilities may be detected by providing the pits with extensive slope movement monitoring systems which provide a supplementary back-up by signalling the operator when an instability is pending. Thus the risks can be reduced in the critical stage of future development through early monitoring. Men and equipment may be pulled out of the pit.

Usually slope monitoring is done by using several procedures, of which, the most important part is sophisticted surveying and geotechnical instrumentation. The performance of the actual monitoring methods is good in situations of gradual failure, specially in the case of circular or planar failures. Some failure mechanisms develope in dynamic fashion, such as toppling or slabbing modes. In these particular situations,the sudden development requires utilization of other monitoring procedures. For a long time, consideration was given to microseismic activities connected with failure modes. The successful application of the microseismic method to underground operations has improved safety with no sacrifice to products or to extraction ratios. In the application of microseismic methods for slope monitoring, concerns were expressed mainly in relation to the different sizes of instabilities. Expected application of the use of a method is to improve and optimize the unloading of potential failure areas in the removal of material from the top of slope walls rather than the clean-up of slides from the bottom of the slide. Several microseismic applications are known for monitoring land slide activity. A case history relates the successful monitoring of highway alignment in Kern Canyon, California, where the speed of corrective action was related to developing the slide activity which was determined with microseismic measurements (Fig. 4).

Significant improvement in technology of source locations has been developed in the United States by U.S.B.M. following several instrumentations

at the Baron open pit mine in Kimberley (1964-1966), at Kennecott Copper Mines and at Liberty Pit.

A second generation of microseismic instrumentation developed for slope monitoring (Fig. 20) is available and was tested for a large open pit operation in the foothills of Alberta. The objective of the field tests undertaken at the Cardinal River Coal Mine was a cooperative effort made by the operator and a joint USBM-CANMET team which evaluated the contribution of microseismic measurement as a supplementary monitoring system to the routine surveying system of Electronic Distance Measurement. The system uses an array of eight geophones linked by cables to a radio transmitter communicating with a receiver unit outside of the pit where the location of the seismic event is given on a printer. The microseismic system was developed at the Denver Research Center and is described in more detail in reports between 1981-1982. Microseismic monitoring was used for 28 days between June and July 1984. Approximately 15 000 events were identified as unique events and about a 1 000 as multiple events with source locations. The image of microseismic activity expressed by the number of events corresponds with the overall movement of the slope, the total displacement, as well as, by the rate of displacement. The variation of microseismic activity is relevant for the increasing of EDM reading from daily reading to hourly frequency. The field test was undertaken in a pit (50-B-C) with very weak rocks and structural discontinuities where the stability condition was marginal mainly for the deepest level of the operation. The expected slope height was of about 144 m and an installation array of seven was operating when the pit reached a depth of about 100 m. The microseismic monitoring was a complementary procedure to the EDM surveying method used in most of the critical slopes in the mine. As expected significant movement were triggered as the operation developed to from 100 to 140 m and the microseismic monitoring was in operation until the observation bench at 90 m depth underwent significance displacement of 2.1 m. At this stage the cable link between the geophones and transmitters was destroyed by debris. About 2500 events were located and the locating program was triggered when microseismic signals were recorded on four geophones. A complete reference on the recorded events and their significance will be publised by a USBM-CANMET joint report in the second half of 1985 and a preliminary presentation on the outcome of the tests has been published in the CANMET report ERP/CRL 85-1(OP).

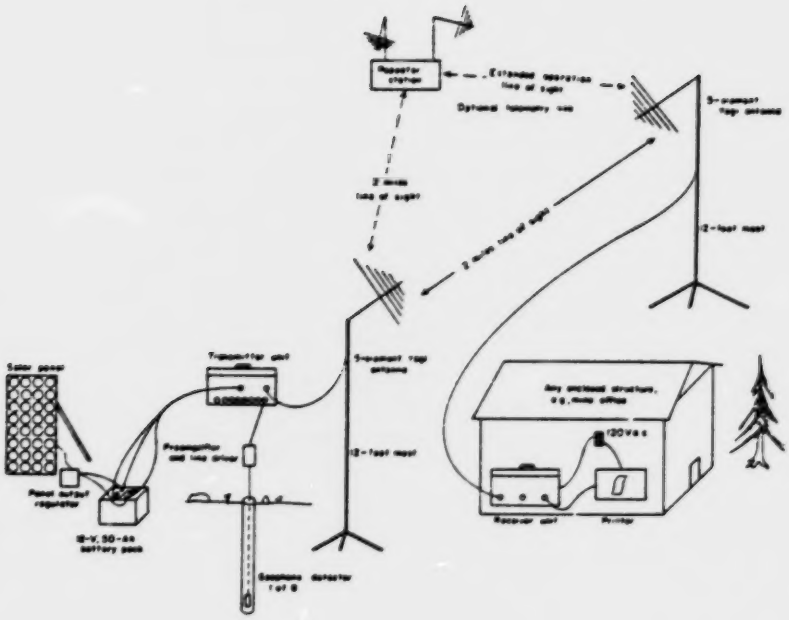


Fig. 20 - Microseismic slope system developed by USBM (11)

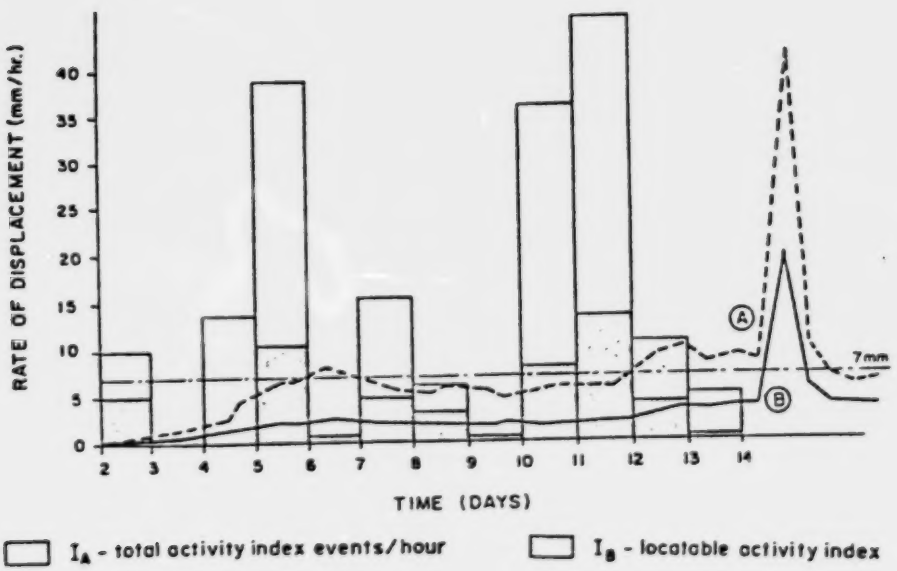


Fig. 21- Correlation between microseismic activity (I_A, I_B) and displacement (EDM Measurement from (21).

A - microseismic event

B - located microseismic events (minimum four arrivals)

Locating many microseismic events can be considered to be a product of successful technology, but practical application in mining still is hindered by the lack of computational power which can draw conclusions on the significance of the emissions in real time. The field tests indicate that the identification of microseismic events can descriminate interferences from most common mining noises such as blasting, transportation and excavation. Careful observation of events recorded during and after blasting in the pit indicate that the equipment has enough protection from collecting "parasitic data". Even the most common mining interferences are avoided. Several other types of interferences were noted, mainly related to climatic and lightening conditions. Some events were still identified as parasitic data mainly when the location was above and very close to the slope. The dynamic aspect of the slope movement which reached a maximum of 12 m in the final stage and with strong distortion on the slope movement may be interfered somehow with the exact knowledge of the topography of the slope. This may be related to movement distortion which had significant direction changes. The rotation of the observation bench during the microseismic monitoring is expressed by a difference in movement of about 1.5 m, which, at later stages, changed direction and the rotation of slope reached a difference in movement of 5.4 m in a opposite direction.

Implementation of microseismic monitoring of slope instabilities for an early warning system in open pit mines is possible but two supplementary steps should be mentioned prior to final recommendation for current operational use. The first instrumentation itself needs better protection from climatic interferences. The second step is to use data processing systems which can provide the decision making support on triggering early warning signals in the pit area. This would require sophisticated location softwares and significant components related to the interpretation of arising data from the microseismic events and fracture development. Several spin-off references are given regarding microseismic monitoring tests near open pit slopes and may be of importance to underground monitoring development.

The monitoring of slopes better defines instability development. The safety factor of the slope varies during the mining operation. The evaluation of the risk could be supported by EDM survey data and through this provide a realistic definition of the activity (Fig. 21). In such risk evaluation and using microseismic methods it is difficult to directly use

concepts developed for underground mining. However, surveying gives the advantage, in open pits that greater information of rockmass movement is available, both before, during and after failure. Microseismic data can then be better correlated with ground movement and the predictability of failure assessed.

Several other technological aspects from field tests may have significance with regard to other monitoring endeavours undertaken for improvement of safety in underground or in open pits.

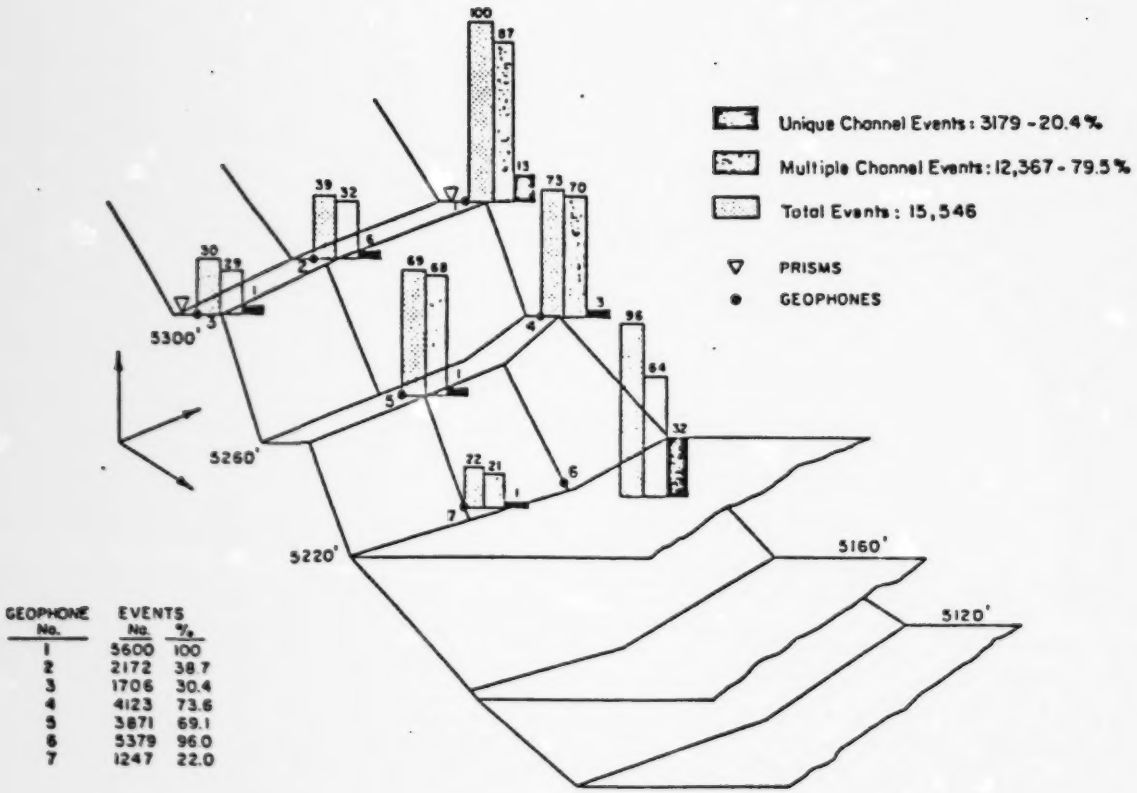
The Cardinal site involved monitoring a significant volume of unstable rock. During the observation period, unique single events and multiple events were evaluated. The comparative analysis illustrates the rate of success that might be expected from multi-channel and single-channel monitors. Even though the number of singular events is relatively small (in comparison to multiple events) the activity in the most active areas of the slope is still well defined by singular events (Fig. 22). The area of significant movements (to 2.1 m) are signalled by 13-30% of the singular events and the area with a slower movement (to 0.5 m) is identified by 1-6% of the singular events. It should be considered that single channel microseismic monitoring can be successful in a well planned test in a very active area. If confirmed, such a conclusion would support also single channel monitors as possible contributors to safety enhancement when mining in unstable areas. Such considerations are of significance for microseismic monitoring in both underground mining and surface operations.

Several other supporting conclusions for microseismic monitoring can be achieved by parallel testing where the early warning procedure is based not only on solely acoustic data but also on geomechanical information.

3.4. LABORATORY AND ANALYTICAL DEVELOPMENTS

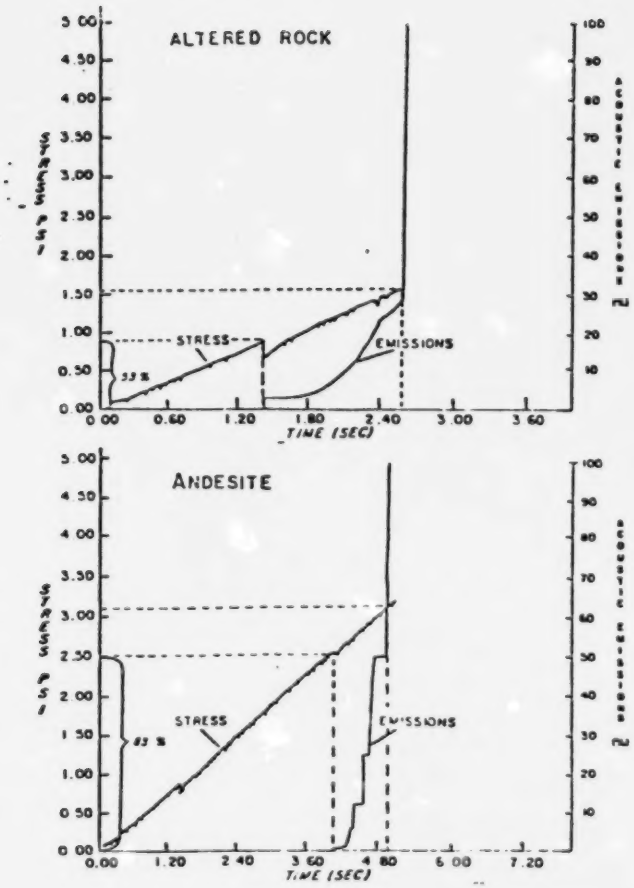
3.4.1. Laboratory Developments

Laboratory measurements complement field testing and can be exemplified by instances such as the rockburst study at Cambell Red Lake Mines (Fig. 23). The aim of such studies is to support and clarify results obtained in the field experiments. Some studies have been conducted to investigate fundamental aspects of acoustic emissions. Baron (1970) has used microseismic emission to determine the point of unstable fracture in specimens under uniaxial and triaxial state of stresses (Fig. 24).



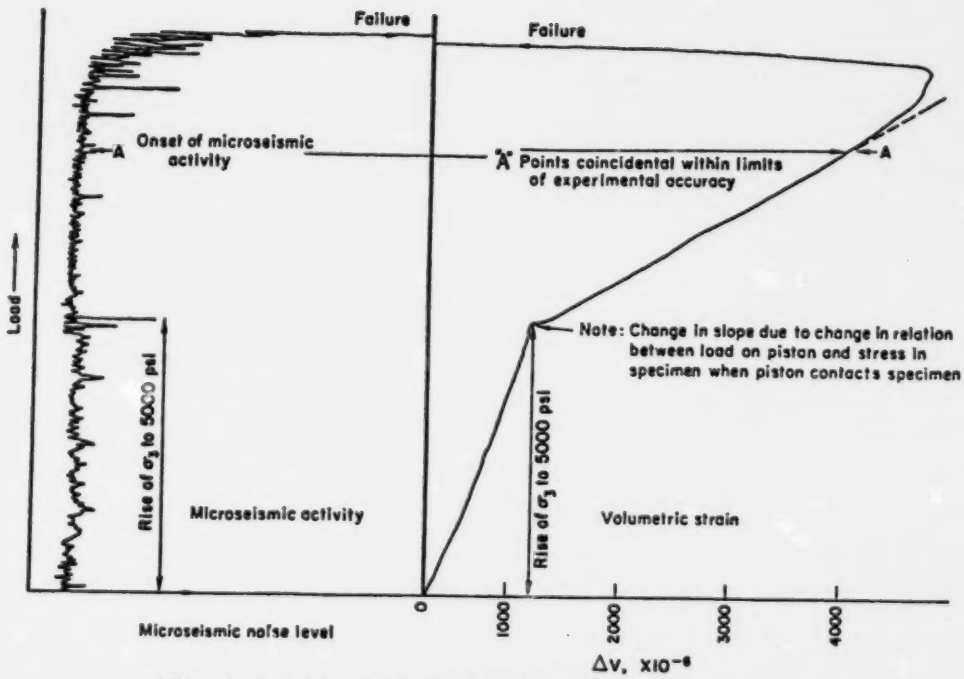
GEOPHONE No.	EVENTS No.	EVENTS %
1	5600	100
2	2172	38.7
3	1706	30.4
4	4123	73.6
5	3871	69.1
6	5379	96.0
7	1247	22.0

Fig. 22 - Distribution of multiple andunique type of events from a microseismic slope monitoring (21)



Uniaxial Stress vs. Acoustic Emissions

Fig. 23 - Laboratory testing of microseismic emissions (28)



Microseismic activity and volumetric strain—syenite specimen, σ_3 = 5000 psi.

Fig. 24 - Modification of microseismic emission during laboratory testing. K. Barron (1970).

Note that laboratory studies are not necessarily fundamental studies. The controlled conditions of testing, environment or material should allow significant contribution to basic and applied studies. Laboratory measurements of AE/MA differ from field studies mainly in respect to frequency range in which emissions are monitored and in the instrumentationalsophistication employed.

H. Reginald Hardy Jr. reviewed (102) the most important areas of the effects of stress level, frequency spectra, source location and mechanisms. Several such studies have already mentioned the relationship between emissions and applied stresses (Fig. 3a).

Most important is the fact that the complexity of the geological materials and the complexity of the behaviour with respect to stress, temperature, cannot be simulated in simple approaches. Significant contributions have used man-made materials to simulate rock-like materials (317) and to simulate, field phenomena such as coal outbursts (315) or others of a complex nature.

3.4.2. Analytical Developments

Several field and laboratory studies have not been successful enough in terms of the investment. This was due to knowledge or practical limitations. Such over-ambitious projects together with fundamental studies represent a significant effort on the part of researchers involved in the area of microseismic and acoustic emissions, and is outlined in Fig. 8. This work is important for the improvement of the rate of success of further microseismic monitoring.

a. Signal processing which includes the physical interpretation, (231) detection and spectral analysis (331), and

b. Hardware related developments. This includes simplification and utilization of new types of materials such as semi-conductors (333) and the definition of limitations of actual transducers (334), or the impact of coupling to rock (336). Several problems are related to the processing of low-level emission signals (232) or source locations (335) discussed in relation to rock bursts in paragraph 3.2.5.

3.5. MICROSEISMIC EQUIPMENT AND INSTALLATION

The monitoring of microseismic activity is based upon the recording of signals given off by the rock in response to mining activity.

The difference between seismic emissions and the type of acoustic emissions of interest is only to the amount of energy released. The energy released is dependent upon the energy stored, which reflects the in-situ stresses and the rate at which this energy can be released or dissipated. The energy release is related to the volume of the rock affected by mining operations, to the volume of mined material and the rate of production. Ideally, the volume of rock monitored should be enclosed by sensors and provide a coverage in three dimensions.

Microseismic instrumentation consists of one to 64 channel equipment. The type of equipment selected is influenced by economic limitations and the geological and mining complexity of the field situation. Such elements control the scale of instrumentation necessary for a useful monitoring. It should be mentioned that the cost of instruments (between Can $60K for an Electro lab type or Can $260K for a Q type system), represents only about 30 to 60 percent of the total installation cost for complex underground instrumentation. Significant expenditures are related to materials such as cables, junction boxes, and other electronics which cost up to 10 to 20 percent of total cost (between 200K to 400K). Labour for installation (20 to 30 percent) and initial operation (10 to 25 percent) should be considered in a realistic cost estimate. The figures are general estimates and should be considered only as a guideline, and are in relation to the degree of sophistication and extent of computer support for fast data analysis. Successful single channel monitoring depends on data acquisition and the use of such data. The equipment available to the Canadian market is a single channel instrument which is represented by the "stress alert" rock stress monitor (RSM) from McPhar Mine System Inc. (cost range 20K). The RSM was tested in several Canadian mines, mainly on a rental basis, with a questionable rate of success in hard rock mines (19, 20), and with good results in a potash (Fig. 13) mine operation. It should be noted that there are differences between the current model and the RM1 model used by Potash Corporation Saskatchewan. Several successful monitorings using similar high-frequency techniques are referenced by U.S.B.M. at different location in the United States (46).

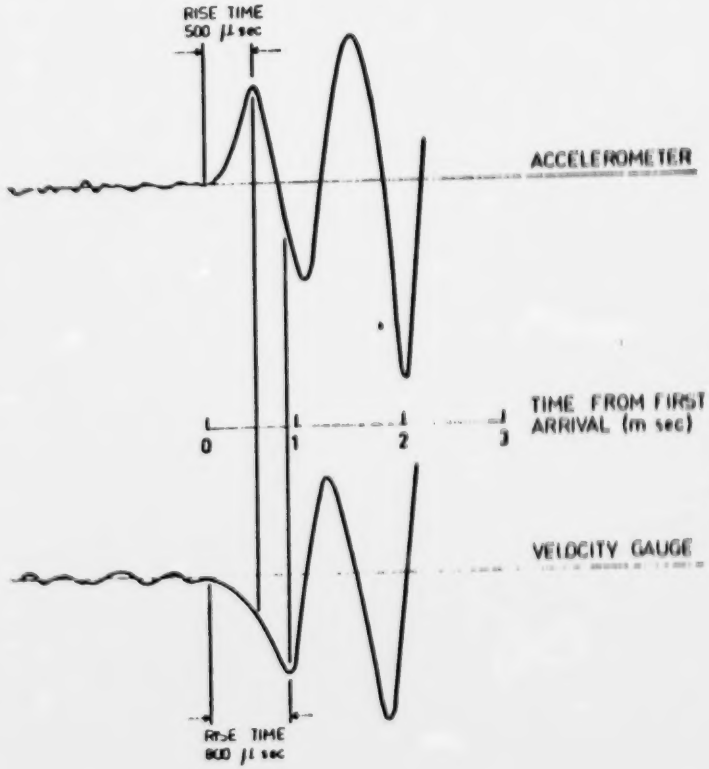
Comparisons between the rate of success by multi channel or single channel monitors is difficult to make. The success probability is obviously lower for single channel observations. A qualitative indication is the field monitoring test made in slope monitoring at Cardinal River Coal Mine in relation to the number of single type events and multiple types recorded (Fig. 22). Even with a significantly lower number of singular recorded events, 20 percent of the emissions were recorded as multiple types (7 geophone array). The indication on the most active area of the slope is also a unique record of events. Details about equipment and instrumentation are mentioned in the paragraph relating to surface mining (Paragraph 3.3). The area of significant movements (up to 1.2-1.5 m) also had 13-30% of the unique events and the area with slower movements (up to 0.5 m) had 1-6% of the unique events. The conclusion of the example shows that single channel microseismic monitoring can be successful in an active area with a well planned test.

The links, subject to improvement, using a simplified instrument concept are transducer/amplifier/readout device/recorder. Some of these are exemplified in Paragraph 3.4.2 and are relevant to transducer installation. Problems related to the amplifier and recorder are considered to be the domain of electronic and physics professionals and these high-tech concerns are not addressed in this review.

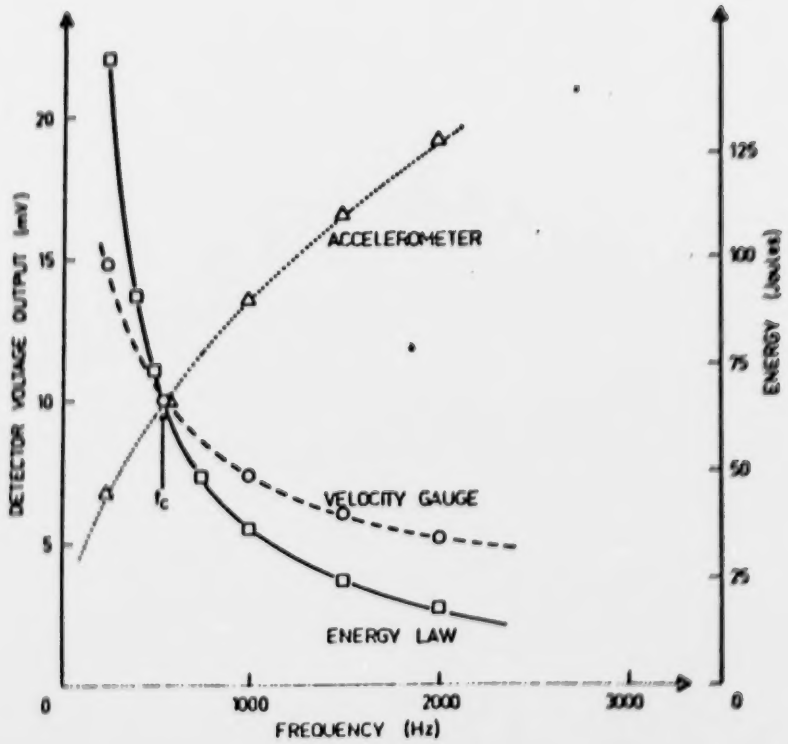
Several problems should be mentioned relating to making a choice between velocity transducers (geophone) or accelerometers. Accelerometers are preferred in relation to broader frequency response, greater dynamic range and more solid construction. The theoretical response of each detector is plotted in Fig. 25 (224). This is of importance to automatic systems because the first arrival is not measured at the break point but is measured at some fixed threshold level above the ambient noise. This illustrates accelerometers are better in representing the first arrival of the shcck wave. Energy-frequency should also be considered (Fig. 25). If the voltage outputs are compared the differences become greater with an increase in frequency. The final element to selecting an instrument is the cost sensitivity ratio.

With regards to the North American market, multi-channel equipment should be mentioned briefly with some information regarding its performance.

a. Microseismic Roof Fall Warning System developed by Integrated Science, Inc., Longmont, Colorado.



Representative detector waveforms for a hypothetical rock noise.



Comparison of rock noise detector responses for an assumed energy law.

Fig. 25 - Elements for transducer selection (224)

b. Microseismic Data Acquisition System - 250 Series Digital Processor developed by Electro-Lab, Spokane, Washigton.

c. Q-Log Seismic Network Processor developed by Dyneer-Springnethor Instruments Inc., St. Louis, Missouri.

A brief description of the performance of the above equipment is as follows:

a. The Microseismic Roof Warning System was developed with the support of U.S.B.M. Microseismic event and energy type data was obtained and documented from 23 mine roof falls with a good probability of applied applications (24). Microseismic events are sensed by a lithium sulphate type transducer. The equipment has coal mine permissibility certification. Some data on successful application in the Sunnyside No. 3 of the Kaiser Steel Corporation are referenced in Fig. 26.

b. The Electro-Lab System is the most used system in Canada and is being used in several hard rock mines such as Falconbridge, Campbell Red Lake, Creighton Mine, as well as, by the Potash Corporation of Saskatchewan. It is micro-processor-based and the logic controls are programmable. The system is flexible and capable of handling up to 64 channels. Using the manufacturer's description, a listing of advantages and disadvantages compared to the Q system, is included in Table 3

c. The Q-Log-AE Equipment is state-of-the-art equipment produced by a very reputable company in the field of seismology. To date, the equipment is used by the University of California at Berkley and at the Nevada Test site. Originally it was designed for battery operation. The system uses a proven real-time distributed processing system. References on advantages and disadvantages of the system are summarized in Table 3. For easy access of manufacturer's literature a list of addresses has been included in Appendix G.

A peculiarity related to the high-tech nature of all systems is that selection of equipment should be made by mining and high-tech professional teams. Track records and consideration on the peculiarities of the mine should be paramount in equipment selection. Cost/sensitivity performance should also be considered.

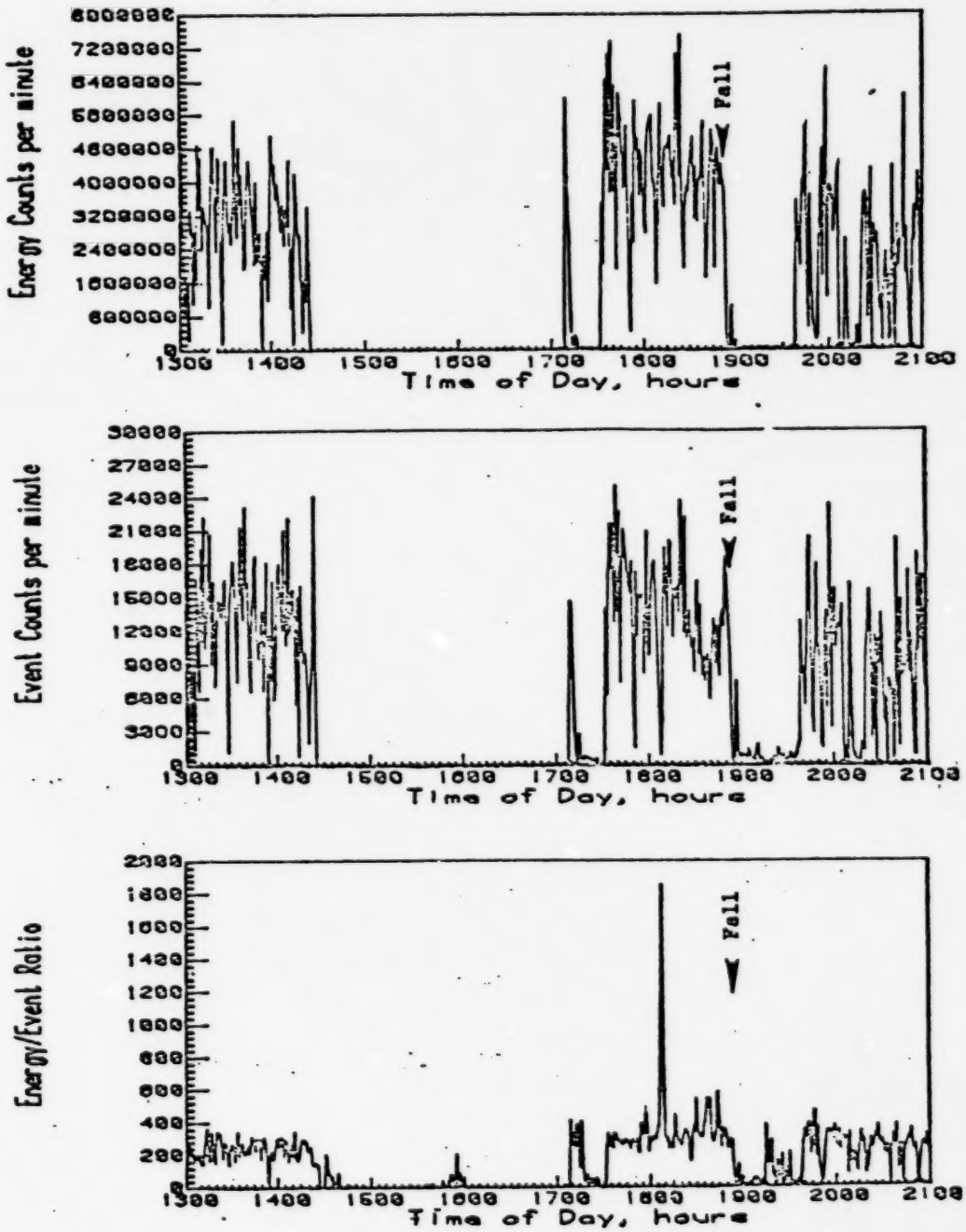


Fig. 20 - Microseismic roof fall data. Sunnyside mine (25)

Table 3 - Information on equipments (summary from manufacturer's documentation)

Electro-Lab 250 MP		Dyneer/Sprengnether Q-log-AE	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Provides event time, arrival times, locations and some size estimate	No discrimination between P&S trigger waves	Provides events, times, locations with statistics, P&S wave properties, stresses, energy released and could be extended if required	Not used yet in mine environment; some usage in similar work
Provide virtually continuous monitoring	Sensors are limited to arrival time use only	Continuous system. Originally designed for battery operation	Expensive
Packaged unit with or without a computer	Sensors can easily be saturated	Internal component processors that are known	Input buffer holds 1 event and rest are lost
Programs for data evaluation have been developed by different mines	Size estimate system under review	Detailed technical information on events for further interpretation	Event analysis time is 40 for 15 channel system with full output
3-4 yrs. experience with system at different Canadian mines			
Simple system with respect to internal operation	Simple location analysis methods by limited input data	Event acceptability criteria are possible for the sensors which record both P&S waves separately	At present, for 15 channel system standard storage is about 100 events for full output
Lower installation cost than Q-Log-AE unit	Location solution has many mathematically sensitive parameters which may lead to poor locations	Multiple styles of source location programs available	Built in computer expected to have graphics, printer-plotter, and increased memory
	Technical backup for electronic problems	Manufacturer will provide technical support, including sensor location if necessary	Some program development may be required because much more event data provided
		Manufacturer is willing to modify to better suit mining needs	
	Requires clean power supply (60 Hz) and environment		
	Cable costs may be high for large numbers of sensors		

It should be mentioned that other equipment is used elsewhere and may be considered, but there is not enough available information on its performance data for this study. It should also be mentioned that a lot of equipment was developed in-house for specific mines, such as the equipment used in South African mines.

3.6. OTHER APPLICATIONS OF MICROSEISMIC OBSERVATIONS

Development of microseismic monitoring is related to other domains than mining production. Several developments are mentioned because they involve natural resource development or similar experiences which may be transferred to the mining industry. Acoustic emission is a well developed area with several applications in material engineering, steel, plastics and structure.

Three domains are civil enginering, soft soil materials and energy resources, as well as other natural resource developments.

Applications to civil engineering refers to material studies specifically in non-destructive testing of concrete (338) and concrete structures, and several successful applications are referenced by RILEM publications for last 15 years. Considered frequently a domain of civil engineering, successful application to the mechanics of soil problems are reported (328). The presence of extended overburden is common to mining operation in areas of open cast mining and mine tailings. Techniques related to mine tailings have much in common with improvement to dam safety problems. AE monitoring frequency ranges, attenuation and signal levels are referred to in Table 4 and reproduced from a Reference Paper (3215). Significant developments related to the fundamentals of AE in soil has been developed by the group of researchers from Draxel University and others (325,326). At this stage AE monitoring of soil masses should not be considered without other geotechnical monitoring procedures. Most aspects need a significant amount of more research, but the results are very promising.

Several interesting monitoring applications are being applied to different technological areas in the natural resources field. In the oil and gas field, applications to fracture propagation in petroleum reservoirs and hydraulic fracturing of gas wells are related to tertiary recovery processes such as fireflood (25).

Table 4a - Generalized Results of AE/MA Properties in Various Tailings Situations

Tailings	Type	Signal Level (g)	Attenuation (dB/m)	Frequency Range (kHz)
Coal		0.05	5-34	0.2 - 4.0
Iron				
	coarse	0.04	4-14	0.1 - 7.0
	fine	0.01	5-21	0.1 - 5.0
Phosphate				
	sand CS-9	0.02	7-21	0.1 - 12.0
	sand M-14	0.04	7-40	0.2 - 7.0
	overburden CS-8	0.05	9-27	0.1 - 5.0
	overburden CS-9	0.05	3-48	0.1 - 7.0
Copper				
	new, sat., fines	0.005	12-17	0.1 - 4.5
	old, dry, fines	0.02	9-33	0.1 - 9.2
	overburden	0.07	9-36	0.1 - 11.7

Table 4b - Generalized Results Grouped According to Particle Size and Manner of Processing

Material	Signal Level (g)	Attenuation (dB/m)	Frequency Range (kHz)
Processed Slimes	.005 - .02	5 - 17	0.1 - 1.5
Cycloned Sands	.03 - .05	7 - 16	0.1 - 12
Waste Overburden	.08 - .13	4 - 28	0.1 - 12

Assessment of nuclear waste disposal sites and the effects of heat on geological material complete the diverse area of microseismic applications. Attention should be given to thermal stress memory type phenomena or the Kaiser effect (Kaiser, 1953) which is the object of several future papers (Appendix E).

Significantly more contributions to the defersification of mechanical rock testing is expected. Evaluation of in-situ stress conditions is being attempted by Dr. R. Hardy with the objective of cost reduction which would allow an increase in the data basis on initial stress conditions (26). Petrographic interpretation of correlation with AE may also be of importance (47).

4. ROLE OF MICROSEISMIC MONITORING IN MINING DEVELOPMENTS

Continuous microseismic monitoring has emerged as a practical approach for assessing structural safety of mines. The monitoring and interpreting techniques have been improved and developed for specific sites in different mining operations. Microseismic monitoring is generally considered to be an independent method of detecting high-stress, failure prone zones; and it does not require a knowledge of rock properties. This speaks well for its application in mining but the success of current applications is not yet satisfactory for the high level of safety required in mining. Difficulties arise due to the complex mechanism of failure of the geological discontinuities. The mechanism is complex where movement/slippage takes place along discontinuities and this response must be addressed for a proper understanding of the behaviour of the mining deposit. This should be studied with respect to other possible mechanisms (e.g., change in potential strain energy).

It is important that microseismic monitoring be controlled by a team with a good knowledge of the local mining and geological conditions. Experience confirms that microseismic monitoring is a mature means of monitoring; its degree of sophistication compared to other standard methods appears to be much more advanced and results in complex instrumentation. The dynamic nature of acoustic emissions requires continuous monitoring and requires observations from at least five different locations. Increases in the size of the monitored area requires a significant increase in the points

of observation. Systems with up to 64 monitor channels are necessary when several signals must be analyzed rapidly for effective early warning. Particularities of using microseismic emission for ground control problems are influenced by the fact that the time lag between the warning and the events is not fully known and is relatively short (Fig. 18).

A measure of successful monitoring in ground control is the ability to relate physical behaviour to microseismic emissions. For example, ground control deformations or support load can be assessed using a model of the field situation for a mining pattern. Such approaches, whether analytical or satistical, indicate a range of acceptable deformations or certain safety factors. Engineering experience allows the use of such elements in verifying the reliability of thresholds.

Such procedures known as "observational methods" are used in most ground control monitoring (Fig. 27). The observational method uses engineering experience to foresee the future ground response to a particular mining development. This includes an evaluation of the factors most likely to control ground response. The primary role of the collected data is to confirm that the predicted mechanism has in fact occurred, and track its progress. This may even allow prediction of the future behaviour during the mining process. Distinct types of data, collected by different monitoring procedures, all contribute to deciding future measures, if high hazards are involved.

In using microseismic emissions in ground control problems one must note that the time lag between the warning and events is either not fully known or is relatively short. It is also clear that microseismic monitoring does not currently have available criteria to evaluate the emission in relation to a critical threshold. In practice, the lack of a predetermined threshold limit is often substituted by an arbitrary site specific criterion.

A site specific criterion can be developed through site specific correlations which would define, for example, number of events, amplitude of events or energy. The warning procedure would use some of these correlations that may be available for the monitored area to draw conclusions by evaluating hazards.

In actual cases the utilization of event monitoring has twin tasks: (a) evaluation of the new observations for their relevance to the existing correlations, and (b) improvement of the correlation for use as a warning

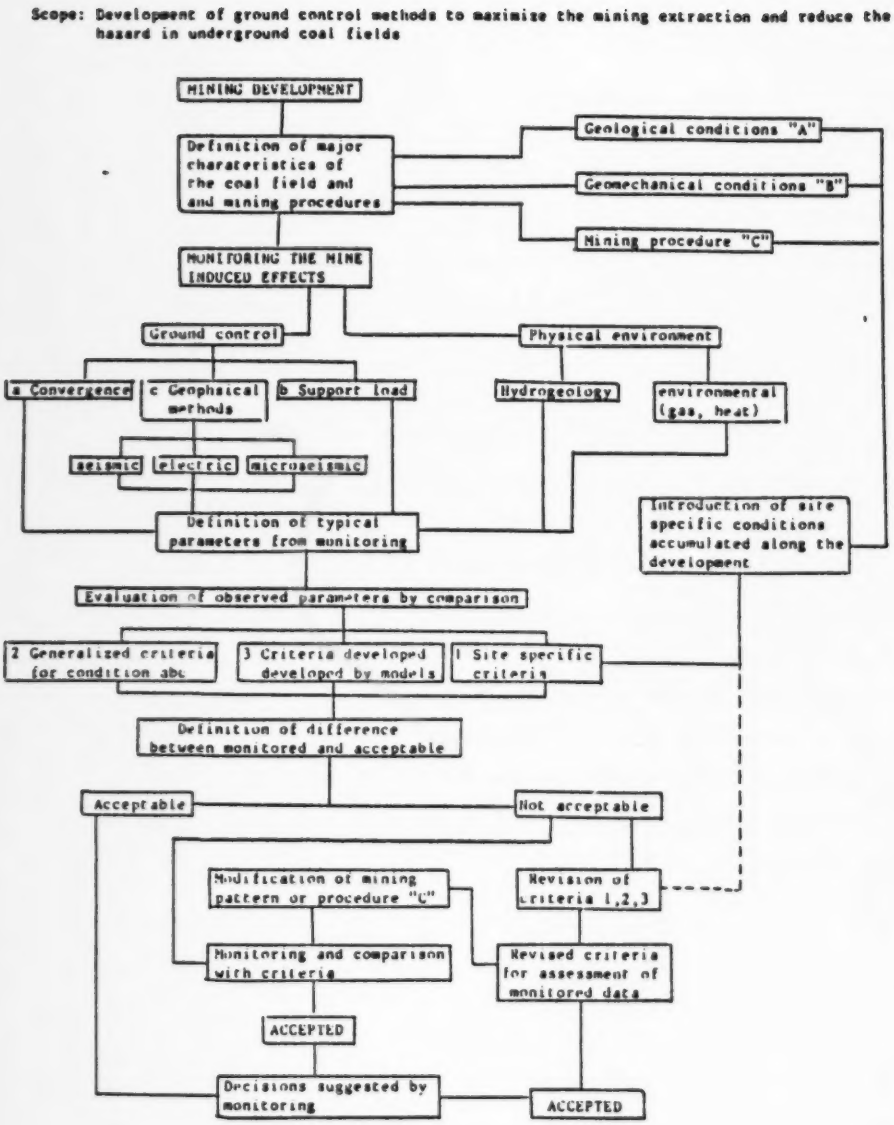

Scope: Development of ground control methods to maximize the mining extraction and reduce the hazard in underground coal fields
MINING DEVELOPMENT
Definition of major charateristics of the coal field and and mining procedures
Geological conditions "A"
Geomechanical conditions "B"
Mining procedure "C"
MONITORING THE MINE INDUCED EFFECTS
Ground control
Physical environment
a Convergence
c Geophsical methods
b Support load
Hydrogeology
environmental (gas, heat)
seismic
electric
microseismic
Definition of typical parameters from monitoring
Introduction of site specific conditions accumulated along the development
Evaluation of observed parameters by comparison
2 Generalized criteria for condition abc
3 Criteria developed developed by models
1 Site specific criteria
Definition of difference between monitored and acceptable
Acceptable
Not acceptable
Modification of mining pattern or procedure "C"
Revision of criteria 1,2,3
Monitoring and comparison with criteria
Revised criteria for assessment of monitored data
ACCEPTED
Decisions suggested by monitoring
ACCEPTED

Fig. 27 - Application of the observational method for ground control and prediction of ground behaviour (38)

signal. The tasks call for a significant amount of data processing which should be carried out in conjunction with the evaluation of warning. In current practice the early warning procedure is still hindered by the uncertainty of the time lag between a percursory event and failure development. The necessity for fast assessment of the revelance of the location of the event and site specific criteria is a possible mean to reduce such difficulties.

The site specific conditions are characterized by three elements: (a) geological conditions, (b) geomechanical conditions, and (c) mining sequences. When comparing site specific criteria for microseismic monitoring developed at different mines with that used in relation to other ground control monitoring systems one can predict methods to be utilized in microseismic monitoring practice (Fig. 28). At this stage, microseismic results are essentially site-specific and the ability to frame more generalized transferrable empirical criteria has not been reached. Under simple geological conditions some results, expressed in terms of stored strain energy or change in the potential energy of the structure studied at one site, may be applicable to other equally simple sites.

Despite this, the results of successful application of microseismic observations related to waste disposal, fluid and gas storage and others should be considered for their applications in mining. Research and development should focus more on methodology than on instrumentation with a view to utilizing microseismic data.

5. CONCLUSIONS

Monitoring of microseismic activity or acoustic emissions can be used to improve the safety of mines. For a complete state-of-the-art information on MA technology reference should be made to the Fourth Conference on MA which will be held at Pennsylvania State University in October 1985 (Appendix E). The knowledge derived from past research together with the development of highly sophisticated instrumentation may increase applications of microseismic methods in mining especially in complex ground control problems.

In considering any contribution of microseismic measurements to mining the following aspects are important.

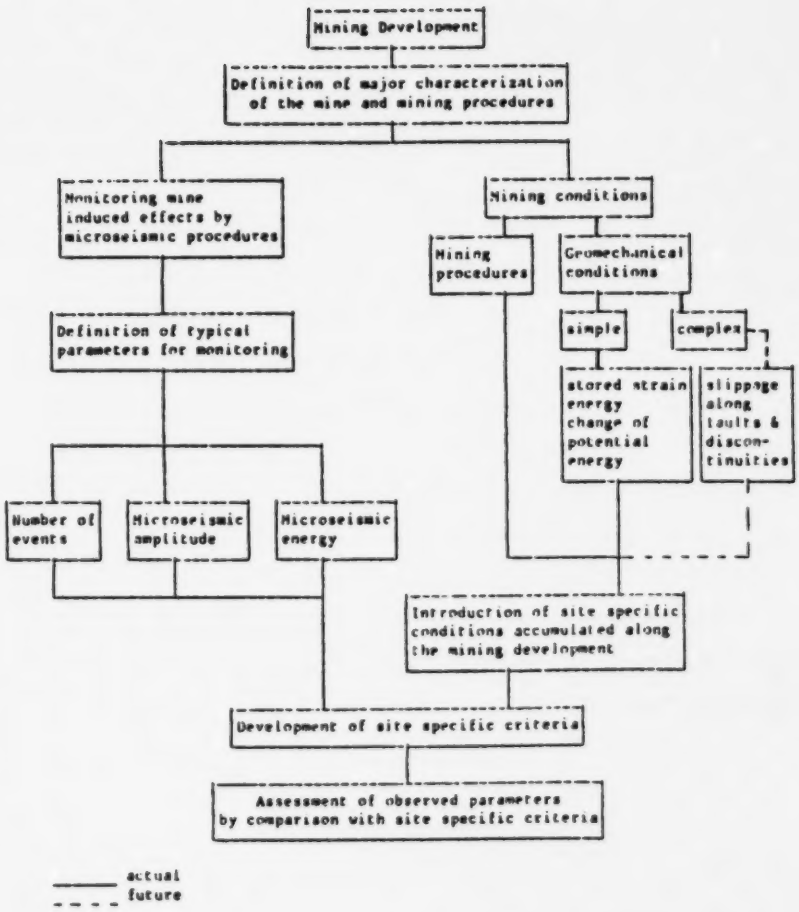

Mining Development
Definition of major characterization of the mine and mining procedures
Monitoring mine induced effects by microseismic procedures
Mining conditions
Mining procedures
Gromechanical conditions
Definition of typical parameters for monitoring
simple
complex
stored strain energy change of potential energy
slippage along faults & discon-tinuities
Number of events
Microseismic amplitude
Microseismic energy
Introduction of site specific conditions accumulated along the mining development
Development of site specific criteria
Assessment of observed parameters by comparison with site specific criteria
actual
future

Fig. 28 - Actual practice of microseismic monitoring and future expected developments (37)

1. Successful microseismic monitoring should not be considered as a unique approach for reducing ground control hazards. The best traditional ground control methods. Successful microseismic monitoring requires a detailed knowledge of the local geological and geomechanical environment.
2. The utilization of microseismic methods requires the support of a team of professionals with technical backgrounds in mining, geology, geophysics and also in technologies related to sophisticated measuring equipment and data processing. Even at this time no short term answers could be expected even with a large-scale project.
3. Application of microseismic technology must be site specific. Decisions for microseismic monitoring can only be made after careful screening of relevant experience, costs, equipment and work organization at a particular site.
4. Significant further research and development would be required before microseismic technology may be considered as a standard method in mining. Significant problems are related to hardware and software for collecting and processing the collected microseismic data. Contribution are expected also from the study of the induced seismic activity aspects of the phenomena and the use of other early warning procedures.

ACKNOWLEDGEMENTS

The author would like to express his sincere thanks to all who have contributed to this work. In particular, the funding of his fellowship by the National Science and Engineering Research Council of Canada is acknowledged. The author also thanks to Calgary Coal Research Laboratory, CANMET, for the support in this project and specially to its staff members.

APPENDIX A: BIBLIOGRAPHY

NOTE ON BIBLIOGRAPHY

Three types of sources of information are referenced as bibliography:

a. The master bibliography published in the Proceedings of the Third Conference "Acoustic Emission/Microseismic Activity in Geological Structures and Materials"; Trans Tech Publications; pp. 739-785. indicated by name of the author and year of publication, e.g. Hardy (1959).

b. Proceedings of the Conference, First (1977) Second (1979) and third (1981) on AE/MA; Trans Tech Publications.
indicated by three or four digits in bracket e.g. (3221) with the following meaning: first digit - number of the conference 1, 2 or 3
second digit - part I, II or III of the volume
third or fourth digit - the number of the paper in the part indicated by the second digit.

c. Specific bibliography included in the Appendix A of the present report, papers not included in (a) and (b).
indicted by one or two digits in a bracket e.g. (12) - indicate the refernece number in the Appendix A.

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APPENDIX B: DEFINITION OF TERMS

*Standard Definitions of Terms Relating to Acoustic Emission, ASTM E610-77, 1978 Annual Book of ASTM Standards, Part 11, pp. 603-605, ASTM, Philadelphia, Pennsylvania.

acoustic emission (AE)--the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from a localized source or sources within a material, or the transient elastic wave(s) so generated. Acoustic emission is the recommended term for general use. Other terms that have been used in AE literature include (1) stress wave emission, (2) microseismic activity, and (3) emission or acoustic emission with other qualifying modifiers.

acoustic emission count (emission count) (N)--the number of times the acoustic emission signal amplitude exceeds a preset threshold during any selected portion of a test.

acoustic emission count rate (emission rate or count rate) ($\dot{N}$)--the rate at which emission counts occur.

acoustic emission energy--the total elastic energy released as acoustic emission.

acoustic emission event (emission event)--a local material change giving rise to acoustic emission.

acoustic emission signal (emission signal)--a signal obtained by detection of one or more acoustic emission events.

acoustic emission signature (signature)--a set of identifiable characteristics of acoustic emission signals associated with a specific test article as observed with a particular instrumentation system under specified test conditions.

active source--a source whose activity increases with increasing or constant stimulation.

arrival time interval (Δt_{ij})--the time interval between the detected arrivals of an acoustic emission wave at the ith and jth sensors of a sensor array.

burst emission--a qualitative description of the discrete signal(s) related to individual emission event(s) occurring within the material. Use of the term burst emission is recommended only for describing the qualitative appearance of emission signals.

continuous emission--a qualitative description of the sustained signal level produced by rapidly occurring acoustic emission events. Use of the term continuous emission is recommended only for describing the qualitative appearance of emission signals.

critically active source--a source whose activity increases at an increasing rate under increasing or constant stimulation.

critically intense source--an intense source whose source intensity continuously increases with increasing stimulation, or with time under constant stimulus (see intense source).

cumulative [acoustic emission] amplitude distribution F(V)--a display of the number of times the acoustic emission signal exceeds an arbitrary amplitude as a function of amplitude (V).

cumulative [acoustic emission] event amplitude distribution $F_e(V)$--a display of the number of acoustic emission events with signals that exceed an arbitrary amplitude as a function of amplitude (V).

differential [acoustic emission] amplitude distribution f(V)--a display of the number of times the acoustic emission signal peak amplitude falls between amplitudes V and V + ΔV as a function of the amplitude V. f(V) is the absolute value of the differential of the cumulative amplitude distribution F(V).

differential [acoustic emission] event amplitude distribution $f_e(V)$--a display of the number of acoustic emission events with peak signal amplitudes between amplitudes V and V + ΔV as a function of the amplitude V. $f_e(V)$ is the absolute value of the differential of the cumulative event amplitude distribution $F_e(V)$.

event count (N_e)--the number obtained by counting each discerned acoustic emission event once.

event count rate ($\dot{N}_e$)--the time rate of the event count.

intense source--an active source whose source intensity consistently exceeds, by a specified amount, the average source intensity of other active sources in the system being examined (see source intensity).

Kaiser effect--the absence of detectable acoustic emission until previously applied stress levels are exceeded.

ring-down count--see acoustic emission count, which is the preferred term.

source activity--that characteristic of an acoustic emission source measured by acoustic emission count or event count.

source intensity (I)--any of several measurable qualities of signals from an active acoustic emission source that may be used to grade the severity of the source. Qualities that are measures of intensity are related to burst signal amplitude and duration; for example, average amplitude per event and counts per burst.

stimulation--any action of applying a stimulus such as force, pressure, heat, etc., to a test article to cause activation of existing acoustic emission sources.

APPENDIX C: PARAMETERS RELATED TO MICROSEISMIC ACTIVITY (DEFINITION AND MATHEMATICAL EXPRESSIONS)

1. Wavelength: (λ) Two points along the wave, separated by the distance, d, are one wavelength apart. Typical points, high or low, pressure etc.

2. Cycle: One complete cycle of change correspond to one complete vibration of the object.

3. Frequency: (f) The frequency is the number of cycles in one second. Cycles per second have been assigned the name Hertz, Hz.

4. Velocity: (c) The speed with which sound waves travel is a function of the elasticity, density which are related to the temperature and pressure.

5. Intensity: Amount of energy passing through a unit surface area. Commonly used to describe levels of acoustic power or intensity is the unit decibel (dB). The decibel is a dimensionless unit used to express the logarithm of the ratio of a measured quantity to a reference quantity.

$$\lambda = c/f$$

$$SPL = 20 \log_{10} \frac{P}{P_0} \text{ dB}$$

SPL - sound pressure level

P - measured sound pressure

P_0 - reference pressure

Pref - 0.0002 η bars (air pressure)

1. Longitudinal waves:

$$v_p = \left(\frac{E}{d}\, g\, \frac{(1-m')}{(1+m')(1-2m')}\right)^{\frac{1}{2}} \text{ m/sec}$$

2. Transverse waves:

$$v_s = \left(\frac{E}{d}\, g\, \frac{1}{2(1+m')}\right)^{\frac{1}{2}}$$

3. Poisson's ratio m' :

$$v_p/v_s = \left[2\, \frac{1 - m'}{1 - 2m'}\right]^{\frac{1}{2}}$$

4. Amplitude of elastic waves:

$$u = u_o\, e^{-\theta x}$$

x - distance; θ = absorption coefficient (1/m).

5. Absorption "θ" :

$$\theta = \frac{8}{3}\, \frac{\pi^2}{v^3}\, \frac{f^2}{d}\, i$$

v - velocity; d - density: i - internal friction; f - frequency
linear relationships for coals, salt, sand, granite.

6. Acoustic impedance:

$$2 = \frac{d}{g}\, v = \frac{\sigma}{v'} \cos \phi' \qquad v' = v_p' \quad \phi = \text{wave pressure}$$

ϕ' - phase angle of shear between the pressure and velocity.
units is acoustical ohm ($g/cm^2 \cdot sec$)

APPENDIX D: ACOUSTIC PROPERTIES OF ROCKS

Acoustic Properties of Some Rocks, Minerals and Metals

Rock, mineral or metal	Apparent specific gravity, kg/m³	Velocity of propagation of longitudinal wave v_p, m/sec	Specific wave impedance $z \times 10^{-5}$, kg/sec·m³
Siltstone	2,600	1,610	42.0
Basalt	2,860	5,400	154.0
Clay	1,500-2,200	1,800-2,400	27.0-52.7
Gabbro	2,900	6,250 (3,380)	181.0
Granite, medium-grained	2,780	4,350 (2,260)	126.0
Gypsum	2,200	1,500	33.0
Halite	2,000-2,200	4,500-5,500	90-128.0
Diorite	2,800	4,580	128.0
Limestone	2,300-3,000	3,200-5,500	73.0-165.0
Ferruginous quartzite	3,000	5,600	168.0
Quartz	2,650	5,225 (3,200)	138.0
Fused quartz	2,650	5,570 (3,515)	145.0
Marble	2,880	4,950	142.5
Sand	1,400-2,000	300-1,300	4.2-26.0
Sandstone	2,100-2,900	2,000-3,600 (2,100)	42.0-100.8
Peridotite	2,800	7,000	196.0
Hornfels	2,800	3,640	102.0
Syenite	2,710	4,950	134.0
Skarn	2,800-3,200	6,100	171-195.0
Shale	2,510-2,720	2,250	56.5-61.5
Coal	1,200-1,500	1,100-2,800	13.0-36.0
Aluminium	2,700	6,260 (3,080)	169
Lead	11,400	2,160 (700)	246
Copper	8,900	4,700 (2,260)	418
Silver	10,500	3,600 (1,590)	378

Note: figures in parentheses indicate the velocity of transverse wave, m/sec.

APPENDIX E: TENTATIVE LIST OF PARTICIPANTS AND PROPOSED PAPERS FOR THE FOURTH CONFERENCE ON ACOUSTIC EMISSION/MICROSEISMIC ACTIVITY IN GEOLOGIC STRUCTURES AND MATERIALS

1. Montoto, M., Ruiz de Argandona, V.G., Galleja, L. and Suarez del Rio, L.M. "Kaiser Effect in Thermo-Cycled Rocks"; Spain.

2. Dunning, D. and Leaird, J.D. "The Kaiser Effect and Frictional Deformation"; U.S.A.

3. Lord Jr., A.E. and Koerner, R.M. "Laboratory Determination of Prestress in Rock and Soil Using AE"; U.S.A.

4. McCabe, W. "Acoustic Emission Monitoring of a Heater Test in Basalt for the Evaluation of Nuclear Waste Disposal"; U.S.A.

5. Lasocki, S. "Some Estimates of Rockburst Danger in Underground Coal Mines for Energy Distribution of MA Events"; Poland.

6. Wong, I.G., Humphrey, J.R. and Silva, W. "Microseismicity and Subsidence Associated with Potash Solution Mine, Southeastern Utah"; U.S.A.

7. Young, P. "Seismic Propagation and Attenuation Mechanisms in Rock Masses: Implications for AE/MS Studies"; Canada.

8. Fujii, Y., Sato, K., Kinoshita, S. and Ishijima, Y. "Microseismic Activity Induced by Longwall Coal Mining"; Japan.

9. Repsher, R.C. "Development and Application of High Frequency Microseismics for a Roof Fall Warning System"; U.S.A.

10. Neumann, M., Mahuch, A. "Microseismic Monitoring of the "F-2" Zone at Campbell Red Lake Mines Limited from July 1983 to February 1985"; Canada.

11. Itakura, K., Nakajima, I. and Ujihira, M. "Consideration of Acoustic Emission Activity from Coal and Gas Outbursts"; Japan.

12. Leighton, F. "An Automated Real Time, Coal Mine Bump Monitor"; U.S.A.

13. Blake, W. "Improving Microseismic Data Analysis by Considering Source Mechanism Energy Release"; U.S.A.

14. Sinha, N.K. "Structure Sensitive Acoustic Emissions in Fresh Water Ice and Sea Ice"; Canada.

15. Will, M. "Combined Evaluation of Seismoacoustical and Mine Data for an Outburst-prone Retreat Mining Area in a Coal Mine"; West Germany.

16. Nittsuma, H., Nakatsuka, K., Takanohashi, M., Chubachi, N. and Yokoyama, H. "Downhole AE Measurement of a Geothermal Reservoir and Its Application to Reservoir Control"; Japan.

17. Gendzwill, D.J. "Some New Algorithms for Microw Earthquake Location"; Canada.

18. Vance, J.B. "The Use of Microseismic Monitoring as an On-line System and as a Trouble-Shooting Tool at the Potash Corporation of Saskatchewan"; Canada.

19. Vance, J.B., Mottahed, P. "Application of High Frequency Microseismic Monitoring in Determining the Behaviour of Salt Under Stress); Canada.

20. Fisher Jr., C. "ME Instrumentatio for Underground Mining Research"; U.S.A.

21. Hente, B., Quijano, A. and Durr, K. "Microseismic Observations in a Salt Mine and Their Relationship to the Min Survey Results"; West Germany.

22. Rowell, G.A. and Brady, B.T. "Acoustic Emissions from Laboratory Rock Bursts with Pictures from High Speed Movies"; U.S.A.

23. Styles, P. "Microseismic Precusors to Spontaneous Outbursts in Cynheidre Colliery, Dyfed, Southwest Wales"; U.K.

24. Nelson, P.P. and Glaser, S.D. "Acoustic Emission Monitoring during Discrete Fracture Propagation in Large Volume Rock Specimens"; U.S.A.

25. Hedley, D.G.F., Bharti, S., West, D and Blake, W. "Rock Bursts due to Fault-Slippage at the Falconbridge Mine"; Canada.

26. Baria, R., Hearn, K. and Batchelor, A.S. "The Monitoring of Induced Seismicity during the Hydraulic Stimulation of a Potential Hot Dry Rock Geothermal Reservoir"; U.K.

27. Nikolaus, J. and Meister, D. "Stress, Strain and Acoustic Emission of Asse-Mine Rock Salt in Laboratory Experiments and In-Situ"; West Germany.

28. Gangi, A.F. and Johnson, B. "An Inexpensive Acoustic Emission Dector/Recorder: Thermal-Cracking Experiments"; U.S.A.

29. Nakamura, J., Tanimato, K. and Tanaka, Y. "Determination of Yield Locus of Soil Using AE Measurements"; Japan.

30. Ohtsu, M. "Fundamental Mechanisms of Acoustic Emission"; Japan.

31. Brink, A.V.Z., Mountfort, P.I. "Microseismic Activity Preceeding Rockbursts Observed at Western Deep Levels Gold Mine"; Republic of South Africa.

32. Khair, A. "Identification of Fracture Intensity and Length, in Coal Blocks Subjected to Dynamic Loading, Using AE and Sonic Techniques"; U.S.A.

33. Dobecki, T.L. "Acoustic Emissions from Hydraulic Fractures in Gas Wells - Long Term Observations"; U.S.A.

34. Carabelli, E., Graziano, F. and Federici, P. "AE in Dam Rock Foundation and MS Survey in the Reservoir Area: Some Years of Study in South Italy"; Italy.

35. MacDonald, P. and Oliver, P. "The Microseismic Monitoring System at Creighton Mine, Inco Ltd."; Canada.

36. Momoh, O.A., Kanduth, H., Campbell, P. and Bawden, W. "AE/MS Montioring in the Noranda Group Mines"; Canada.

37. Subbaramu, K.R., Krishnamurthy, R. and Rao, B.S.S. "Establishment of Surface and Underground Seismic Network and Its Monitoring of Rockburst Activity at Kolar Gold Fields"; India.

38. Yoshioka, H., Michihiro, K., Fujiwara, T. and Hata, K. "Strain Dependende of the Kaiser Effect in Various Rocks"; Japan.

39. Cristescu, N. "An Elastic-Viscoelastic Constitutive Equation for Rocks and the Associated Mechanical - AE/MS Analogy"; Romania.

40. Li, D. "Application of AE Techniques to Prediction of Mining Structure Failure"; People's Republic of China.

41. Yu, J. "Present Status of AE Studies in Geologic Structures and Materials in China"; People's Republic of China.

42. Hardy Jr., H.R., Zhang, D. and Zelanko, J. "Recent Studies Relative to the Kaiser Effect in Geologic Materials"; U.S.A.

43. Kimble Jr., E.J., and Hardy Jr., H.R. "Development of the Mark II Mobile Microseismic Monitoring Facility: U.S.A.

44. Belesky, R. and Mrugala, M. "Recent Geotechnical Applications of the Acoustic Emission/Microseismic Technique"; U.S.A.

45. Mrugala, M. and Belesky, R. "Recent Geotechnical Applications of the Acoustic Emission/Microseismic Technique"; U.S.A.

46. Ge, M.C. "Effect of Velocity Data Quality on Source Location and Analysis of Optimum Transducer Array Geometry"; U.S.A.

47. Ersavci, N. "Recent Studies Relative to the Application of the McPhar Rock Stress Monitor"; U.S.A

48. Lepper, C.M. and Vladut, T.I. "Early Warning of Slope Instabilities by Microseismic Monitoring"; U.S.A./Canada.

APPENDIX F: ROCKBURST ACTIVITY

ROCKBURST ACTIVITY

FALCONBRIDGE MINE - JUNE 20 - 23, 1984

SUMMARY REPORT OF THE TECHNICAL COMMITTEE

July 5, 1984

1.0 TERMS OF REFERENCE

(a) To evaluate the mechanisms and causes of recent rockbursts at Falconbridge mine.

(b) To advise on future mining activity and research investigations at Falconbridge mine.

After several underground visits and delibrations over 3 days, the committee feels that it has satisfied the above terms of reference.

2.0 MECHANISM OF ROCKBURSTS

Of the three mechanisms considered by the committee, namely stored strain energy, change in potential energy and slippage along faults, it appears that slippage along faults was the most likely mechanism. This conclusion is based on the following considerations:

(a) Most of the observed damage underground was caused by shock waves radiating from the seismic events.

(b) There were apparent movements along the Ore Pass Fault and the #1 Flat Fault.

(c) Movement of the order of 0.5 to 2 inches along 500 feet of these faults would be sufficient to release this energy (3.2 to 3.5 Local Richter Magnitude).

(d) Structural damage to the mine was less severe than might have been anticipated from the magnitude and number of seismic events.

The committee recommends that additional research be done to confirm the fault-slip mechanism. The study should include driving a drift to the origin of the major rockburst. It is not possible to identify the exact triggering mechanism that initiated the rockburst sequence. The committee emphasizes that the rockbursts experienced on June 20-23, 1984, are distinctly different from previous rockbursts at this mine.

The last major rockburst occured on June 23, 1984, and experience indicates that fault-slip seismicity is followed by a period of inactivity due to the relaxation of the rock mass. Notwithstanding this, it is recommended that the mines future action plan should be restricted as indicated in the following section.

3.0 FUTURE MINING ACTIVITY

(a) East Mine was not affected and is remote from the rockburst zone. Therefore, there are no technical reasons why it should not be reopened.

(b) Similarly, the areas above the 2,800 level and below the 4,700 level at Falconbridge Mine were not affected. However, a structural analysis should be done on a stope-by-stope basis before reopening.

(c) The technical committee recommends that the area between 2,800 and 4,700 levels containing the rockburst zone and the Hoistroom Pillar requires a more detailed technical evaluation before any mining can be considered. This should include:

- computer modelling
- structural evaluation of the faulting
- monitoring of stresses and displacements
- mine-wide seismic network

4.0 RESEARCH

Rockbursts are recognized as a complex problem worldwide and no complete solutions exist. Progress at Falconbridge will best be accomplished if a concentrated and continuing research effort is devoted to their problem. This will require the cooperation of both levels of government and the mining industry as well as international cooperation with other countries experiencing rockbursts.

A list of the committee members is attached.

TECHNICAL COMMITTEE MEMBERS

1. Dr. D. Hedley: Research Scientist, Canada Centre for Mineral and Energy Technology, Elliot Lake Laboratories.

2. Mr. V. Pakalnis: Chairman, Rock Mechanics and Strata Control Committee of the Canadian Institute of Mining and Metallurgy.

   Mr. Pakalnis has worked in ground control for a number of years and is presently Chief Mining Engineer with the Ministry of Labour.

3. Mr. E. Hollop: Chief, Ground Control Division, Denver Research Centre, U.S. Bureau of Mines.

   Mr. Hollop has worked with rock mechanics and rockburst problems for a number of years.

4. Dr. W. Blake: Private Consultant. Dr. Blake is a specialist in rockburst phenomena and microseismic systems and worked for the U.S. Bureau of Mines for a number of years.

5. Mr. C. Graham: Senior Ground Control Engineer, Ministry of Labour.

   Mr. Graham is involved in a number of ground control programs at the mines in Ontario.

6. Mr. D. Ortlepp: Group Rock Mechanics Engineer, Rand Mines, S. Africa.

Representing Falconbridge Limited

Mr. S. Bharti: Chief Rock Mechanics Engineer, Falconbridge Limited, Sudbury Operations.

Mr. D. West: Ground Control Supervisor, Falconbridge - East Mines.

APPENDIX G: INFORMATION ON MICROSEISMIC INSTRUMENT MANUFACTURERS

1. Electro-Lab
   Building 10
   Spokane Industrial Park
   Spokane, Washington 99216
   U.S.A
   Tel: (509) 928-0939

2. Dyneer
   Srengnether Instruments, Inc.
   A Subsidiary of Dyneer Corporation
   4150 Laclede Avenue
   St. Louis, MO 63108
   U.S.A.
   Tel: (314) 535-1682
   Tlx: 44-2399
   Cable: SPRENCO

3. Acoustic Emission Technology Corporation
   1812J Tribute Road
   Sacramento, CA 95815
   U.S.A.
   Tel: (916) 927-3861
   Tlx: 171-356

4. Mine Innovations Inc.
   5710 West 36th Street
   Mineapolis, MN 55416
   U.S.A.
   Tel: (612) 926-1517
   Tlx: 0029-0208